Design of Cathodic Protection of Offshore Structures/Màster

Treball Final de Master

Facultat de Nàutica de Barcelona
Universitat Politècnica de Catalunya

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To my mother, father and sister...

Resum

Basat en el punt de vista del medi ambient, la corrosió és un esdeveniment ambiental que cal per mantenir l'equilibri natural. Des del punt de vista de lenginyer, aquest equilibri natural sobserva com un atac natural perjudicial a un metall per una reacció electroquímica. Aquest atac natural té diversos tipus, com la corrosió uniforme, per esquerdes o per picades, i dóna com a resultat una pèrdua de material severa, fet que contribueix a la pèrdua de producció ia l'augment dels costos de manteniment, reparació i reemplaçament, així com els costos de restauració. Per tant, la prevenció de la corrosió és molt important per al metall que s'aplicarà a una plataforma marina.

El mètode més típic per prevenir la corrosió de les superfícies d'acer de les estructures a alta mar és utilitzar un sistema de protecció catòdica i un revestiment eficaç. Els mètodes de protecció catòdica funcionen convertint les àrees actives d'una superfície metàl·lica en àrees passives, col·locant-les així al càtode d'una cel·la electroquímica. Mentre s'apliquen aquests mètodes de protecció, també es pot fer servir un recobriment. La intenció del recobriment és regular una via electrolítica posant una barrera entre la superfície metàl·lica i la solució corrosiva. Abans de discutir els detalls del disseny, en aquesta investigació s'esmenten tant la protecció catòdica de corrent impresa com la protecció catòdica d'ànode de sacrifici, així com la combinació de CP amb recobriment. El mètode de l'ànode de sacrifici (SACP) s'aplica amb un metall que té un potencial menor que el metall de l'estructura que cal protegir. Per tant, els ànodes de sacrifici provoquen una corrosió del metall més ràpida que la que té l'estructura metàl·lica i brinden protecció contra la corrosió. Mentre que, com que el mètode de corrent impres (ICCP) produeix el seu corrent per mitjà d'una font externa, no hi ha necessitat d'ànode de sacrifici com s'aplica a SACP. Sobre aquesta base, tots dos mètodes de protecció catòdica tenen diferents requisits i criteris de disseny. Aquestes diferències entre SACP i ICCP s'esmenten en aquesta investigació en termes d'instal·lació del sistema, efectes ambientals, combinació amb recobriment i requisits d'acer i ànode.

Durant l'aplicació d'aquestes proteccions, tota la vida d'aquesta protecció per a l'estructura en qüestió es denomina Vida Anticipada. Encara que és difícil complir completament la vida prevista, el càlcul del disseny s'ha de fer d'acord amb aquesta vida útil i els paràmetres requerits (p. ex., massa de l'ànode, tipus d'ànode, sortida de corrent, etc.) s'han d'obtenir correctament . Si no, la distribució d'ànodes podria no ser eficient per desplegar tota l'àrea a protegir. Com a exemple de càlcul de disseny per a una àrea submergida d'un sistema, es va considerar el disseny de SACP per a una estructura hipotètica de parc eòlic ubicada a les Illes Canàries i es va seguir la recomanació de disseny DNV-RP-B401 com a guia en aquesta investigació. Els paràmetres inicials dels càlculs de disseny (per exemple, salinitat, massa inicial, temperatura, etc.) es van obtenir de fonts governamentals i projectes anteriors a les Illes Canàries. La intenció principal d‟aquest càlcul és explicar el procés de disseny de protecció catòdica utilitzant la recomanació DNV i determinar les diferències entre estructures recobertes i no recobertes en termes de requisits d‟ànode. Segons els resultats, l'ús d'un ànode d'alumini independent, que té un factor d'utilització més gran en comparació amb altres tipus d'ànodes, a més del recobriment de Categoria III basat en la guia DNV, condueix a una menor quantitat de massa d'ànode. Per tant, el consum d'ànodes i les despeses es minimitzaran i hi ha una distribució d'ànodes més adequada a través de les distàncies més llargues a causa de la caiguda més baixa d'IR.

ABSTRACT

Based on the standpoint of the environment, corrosion is an environmental occurrence that is required to maintain the natural balance. From the engineer's standpoint, this natural balance is observed as a damaging natural attack on a metal by an electrochemical reaction. This natural attack has various types such as uniform, crevice or pitting corrosion and it results in severe material loss, which contributes to lost production and increased maintenance, repair, and replacement costs, as well as restoration costs. Hence, prevention of corrosion is quite significant for metal to be applied in an offshore platform.

The most typical method of preventing corrosion from steel surfaces of offshore structures is to use a cathodic protection system and effective coating. The Cathodic Protection methods work by converting active areas on a metal surface into passive areas, thus putting them into the cathode of an electrochemical cell. While applying these protection methods, a coating may also be employed. The intention of coating is to regulate an electrolytic pathway by putting a barrier between the metallic surface and the corrosive solution. Before discussing the design details, both Impressed Current Cathodic Protection and Sacrificial Anode Cathodic Protection, as well as the combination of CP with coating are mentioned in this research. The sacrificial anode method (SACP) is applied with a metal having a lower potential than the structure metal to be protected. Thus, sacrificial anodes result in quicker corrosion on metal than structure metal has and protect against corrosion. Whereas, as Imthe pressed current method (ICCP) produces its current by means of an external source, there is no need for sacrificial anode as it is applied in SACP. On this basis, both cathodic protection methods have different requirements and design criteria. These differences between SACP and ICCP are mentioned in this research in terms of installation of the system, steel and anode requirements, combination with coating, and environmental effects.

While applying these protections, the entire life of this protection for the structure concerned is cal as "Anticipated Life". Although it's difficult to completely meet the anticipated life, design calculation must be done in accordance with this design life and required parameters (e.g. anode mass, anode type, current output, etc.) must be obtained correctly. Otherwise, anode distribution might not be efficient to deploy the entire area to be protected. As an example of design calculation for a submerged area of a system, SACP design was considered for a hypothetical wind farm structure located in Canary Island and DNV-RP-B401 design recommendation was followed as guidance in this research. Initial parameters of design calculations (e.g. salinity, initial mass, temperature, etc.) were obtained by governmental sources and previous projects across Canary Island. The main intention of this calculation is to explain the design process of cathodic protection using DNV recommendation and determine the differences between coated and uncoated structures in terms of anode requirement. According to results, the use of stand-off aluminum anode which has a greater utilization factor compared to other anode types in addition Category III coating based on DNV guidance leads to a lower amount of anode mass. Thus, anode consumption and expenses will minimize and a more suitable anode distribution exists through the longer distances due to lower IR drop.

Keywords: "Corrosion Control", "Sacrificial Anode Cathodic Protection", "Cathodic Protection Design Criteria", "Impressed Current", "Anode Calculation"

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Nomenclature

General Variables

- V Volt
- Ω Fluid domain
- ρ Density of fluid
- t Time
- F Faraday Constant
- W Weight

Corrosion Variables

- CP Cathodic Protection
- Iccp Impressed current cathodic protection
- Sacp Sacrificial anode cathodic protection
- n_c Polarized potential
- i_L Limited ion diffusion
- i Current
- n_A Polarized potential
- i_0 Current to be activated
- i_a Corrosion rate
- i_c Current density
- Z Valency of electrons
- R Anode Resistance
- L Driving Force
- E_{cor} Corrosion potential
- E_{eq} Equilibrium potential
- I_c Current demand
- A_c Area to be protected
- f_c Coating breakdown factor
- t_f Design life
- u Anode utilization factor
- ϵ Electrochemical capacity of design
- ε_a Circuit design potential of anode selection
- I_a Current output
- m_a Anode mass
- C_a Current capacity

- I_{cor} **Corrosion Density**
- **SRB Sulphate reducing bacteria**
- **SCC Stress corrosion cracking**
- **LME Liquid metal embrittlement**
- **HIC Hydrogen induced cracking**
- **CRA Corrosion Resistant Alloys**

Material Variables

- **SS Stainless steel**
- **CS Carbon steel**

Chemistry Variables

- **Al Aluminium**
- **Mg Magnesium**
- **Cr Chromium**
- **Mo Molybdenum**
- **Ti Titanium**
- **N Nickel**

CHAPTER 1

1) CORROSION

1.1. Introduction to Corrosion

Corrosion is the degradation of a metal as a result of chemical or electrochemical reactions occurring in its surroundings. Furthermore, corrosion is an electron transfer process that is a charged metal ion is formed while an uncharged metal atom loses one or more electrons as follows;

$$\mathrm{M} \rightleftharpoons \mathrm{M}^{+} + \text{electron}$$

This process must first be examined at a microscopic level in order to fully comprehend it. A corrosion cell made up of four components is required for the chemical reaction to take place. Potential corrosion can be defined as follows;

1) A cathode side where electrons are gattered.
2) An anode side where electrons are given off and leading to loss of metal.
3) A metallic circuit that is created by the structure.
4) An electrolyte area where anode and cathode are interacted with each other by submerging.

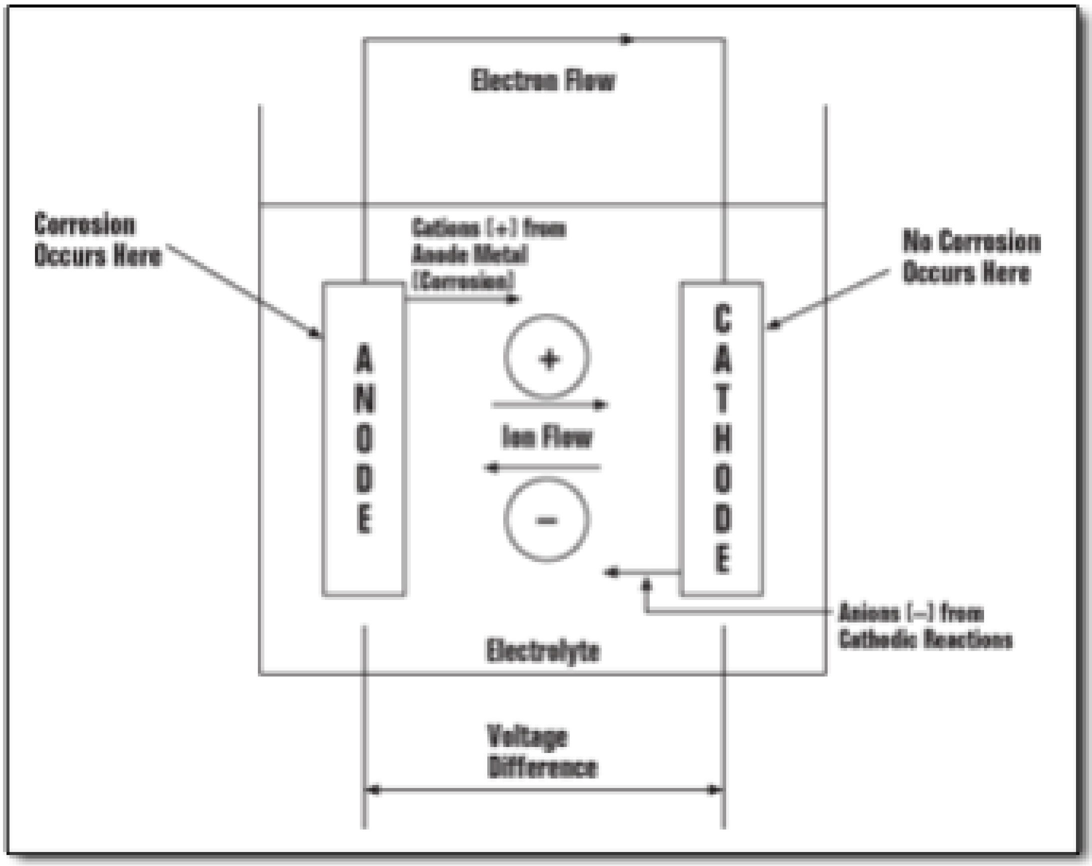


Figure 1. - Corrosion cell explaining the relations of the four key components of an active cell [5]

The four components as it seems above are a circuit in which allows corrosion to take place due to potential difference and tendency of electron transfer from anode to cathode side through the metallic path. As a result of this reaction anode system expose corrosion.

Metals tend to manage electricity. If the environment where metals are to be placed is also good conductive, then corrosion will occur through electrochemical factors. It should be noted that corrosion only occurs when metals interact with its environment. For more information, metal or alloy must be unstable with its environment. Hence, changing the environment of the metal could be an efficient way of corrosion prevention. However, the offshore environment can not be changed based on its electrochemical factor. The only way of prevention is using more suitable materials and applying for protection. For example, wrought iron would be suitable for the urban environment but the use of wrought iron will cause corrosion offshore due to the effects of the salt of the ocean.

Corrosion and corrosion prevention costs are around 5.0 percent of a country's gross national product, resulting in a huge economic factor to companies. The entire cost of corrosion in the oil and gas industry is projected to be $1.372 billion per year. Compared to old projects, current Offshore Projects are projected in a hazardous environment including more factors that leads to corrosion impact. Component life must be improved due to the rising difficulty of maintaining components in more remote and demanding environments. Components with improved corrosion resistance are now required because they extend service life and decrease the need for costly maintenance.

The most efficient time to prevent corrosion is during the design phase. As a result, the designer must have a thorough understanding of corrosion concepts as well as specialized knowledge of the environment and materials relevant to their field of design. The use of proper design eliminates the need for costly retrofits. Following that, the commissioning and operation of plants should be done with corrosion protection in mind. [3]

1.2. Control Of Corrosion

In this part, corrosion was defined briefly as the interaction between metal and its offshore environment, and factors leading to corrosion will be mentioned separately in the later sections, such as the amount of attack concerning metal's thickness, types of corrosion (Pitting, Crevice) and corroded area of surface, in order to discuss those in accordance with corrosion control. It's obvious that corrosion rate is a vitally important factor in which regulates the life duration of structure. Even if the corrosion rate has a tolerated amount, engineers have to consider that it also depends on the thickness of the metal, the interaction of metal and environment, etc. In other words, all the factors must be reviewed in order to obtain control of corrosion.

By using special metals for the structure, corrosion control can be thought of as a reaction regulator, which means, the mechanical and physical features of the metal can be provided in the whole life duration of the structure. While applying this process, the life of this structure is called " Anticipated Life" and it should be noted that this is not the absolute time of the process. On the other hand, though engineers can be told according to planned time that operation should last, it can be corroded much earlier or some extra services can be required. There is no restriction for the cost, however, although structures can be designed to be 10-years of anticipated life, it's completely impossible to design a facility that maintenance is not required during 10 years. Hence, spending more money in order to achieve more protection may lead to spending unnecessary money. Due to the fact that corrosion is an interaction between metal and its environment, these two factors must take place to control. Hence, control could be provided by selecting suitable metals or alloys rather than selecting all other materials or acting of the metals against non-metal materials. The other factors are, control of corrosion can be provided by the resistant materials or the materials that decrease the risks of the environment by means of applying corrosion inhibitors, changing the chemical reactions, avoiding sea pollution, shifting the temperature or velocity etc.

The selection of metal and alloy can be changed according to companies and their work but the resistance of metals against corrosion can not be neglected. Also, the availability of the metal is significant and companies should find a factory that would also be able to manufacture the same metal next years. For instance, although 18%Cr – 8% Ni stainless steel are more expensive than 17% Cr stainless steel, the former are being manufactured more than the latter and it's also problematic to weld the second one, hence the first one is more useable. Concerning to cost, this manufacturing and also delivering costs should be considered.

It should not be considered that finding metal as cheap as it can, will be a good choice to avoid unnecessary expenses. For example, using platinum can be seen as unnecessary expenses but applying for certain parts of the structure will be a profitable investment. Even so, mild steel which can be found easily and has enough corrosion resistance is more preferable to platinum for the offshore structures, just in case cathodic protection or an effective coating can be designed [15].

1.3. Polarization

Polarization is the process that turning a material’s normal potential into more positive or more negative through an external source. When an anode and a cathode are electrically coupled, the anode's lower standard potential acts as an external driving force, causing the cathodes to transfer, or polarize, towards a more negative potential.

It may be considered that materials with more negative energy have more tendency to corrode, however, the amount of negative energy does not have a direct relationship in this way. To give an example, the negative energy potential of Aluminum is -1.662V which makes it a quite active metal, however, kinetic energy during the reaction or its corrosion rate is not as high as its potential. This is why it’s not used in the structural parts in which more dangerous or corrosion might spread around fast. For more information, to give an opposite example of Aluminum, copper (Cu) can be reviewed. Although Cu has a higher potential compared to Aluminum (+0.337 V), it corrodes higher than Aluminum does. In short, corrosion rates are not only dependent on potential, there are many various reasons which may affect the rate of corrosion, as mentioned in the corrosion Rates title.

Hence, polarization is the combination of such relationships among current and potential that is dependent on many factors in the way of linear or non-linear. Polarization can be either cathodic or anodic, and it can be modulated by concentration or activation as mentioned below.

1) **Concentrated Polarization:** If there is enough component to undergo a reaction, the corrosion process can be limited by this amount and chemical reaction can be concentrated based on these components. As the components start consuming and transfer is slow, this polarization is also known as Overpotential Diffusion. For more information, the rate of ion diffusion on the metallic surface affects the increase of reaction rate. This ion rate is limiting current in other words and can be shown as i_L. In this equation 1 below, the relation of polarization response can be described.

$$\eta_C = 2.303\frac{RT}{nF}\log(1-\frac{i}{i_L}) \tag{1.3.1}$$

$Where;$
η_C : $polarized\ potential$
i: current
i_L: limited ion diffusion

2) **Activated Polarization:** The potential difference above the equilibration value required to produce currents based on the energy activation of a redox reaction is known as activation polarization. The activation energy is necessary for electrons to be transported from electrodes to the analyte. Furthermore, the characteristics that are part of generally all

electrochemical reactions and are inherent to kinetics are referred to as activation polarization. The reaction of hydrogen gas can be a good example of this. This is a straightforward reaction, and the pace at which hydrogen ions are transformed into hydrogen gas depends on several variables, including the rate at which electrons are transferred into hydrogen ions. This reaction is also called hydrogen overpotential.
In order to start the chemical reaction, the required activation energy for polarization must be achieved. According to this reaction activated polarization can be described by equation 2 shown below.

$$\eta_A = \beta log \frac{i}{i_O} \tag{1.3.1.}$$

Where;

η_A : $polarized\ potential$

i_O : $electric\ current\ to\ be\ activated$

Both activated and concentrated polarization equations contain the constant terms for each metal in which can be presented and the slope of the curve can be obtained. This slope is named as Tafel Slope which is known very well among the corrosion science community. This slope is conventional in order to evaluate corrosion behavior and obtain a relationship between polarization resistance. The essential principle of this process is to obtain the first reading of potential by measuring without current that is interacted with working electrolyte or metal of interest. Then the working electrolyte starts polarizing by means of galvanostatically, potentiodynamically, or potentiostatically and becomes more negative or positive. Finally, the current response can be obtained by this polarization and then an essential diagram of metal can be obtained.

The other useable way of polarization is monitoring the corrosion to evaluate corrosion rate. This technique is called Linear polarization resistance and by applying this technique a plot can be achieved which includes the potential applied and its current response. Hence, it can be noted that polarization resistance is the slope of the curve which is obtained by the proportion of potential and current response. To give a before and after example for polarization resistance Figure 2 and Figure 3 are below. In these figures, it changes of carbon – steel rebar can be noted by the slope which is turning into almost a straight line by the time. By following this slope, the parts in which severe corrosion occurred can be observed.

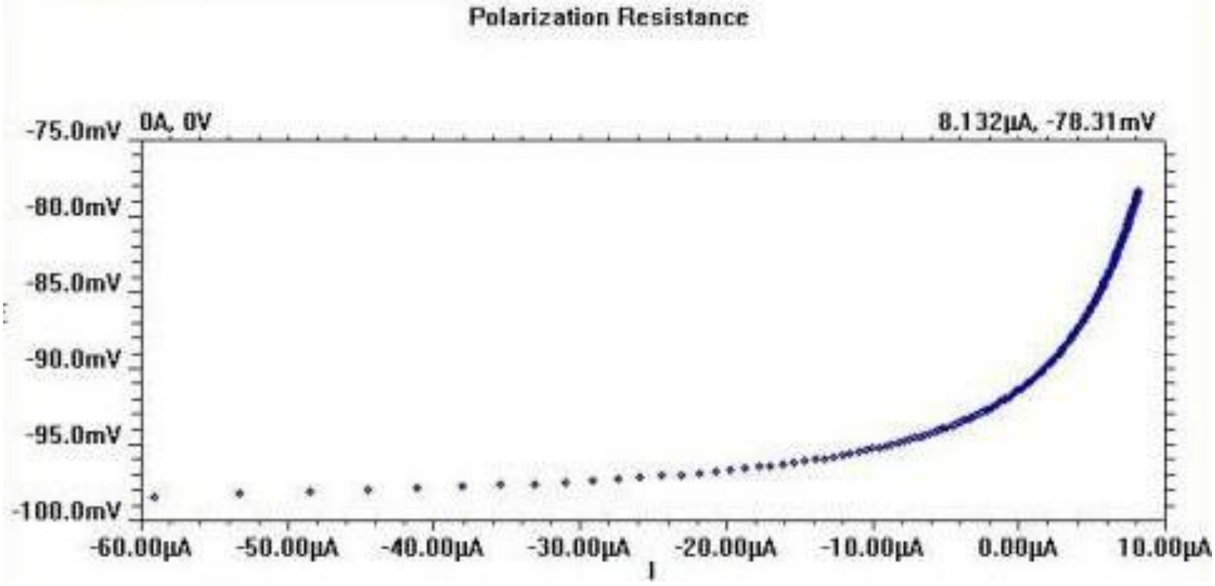


Figure 2.The diagram of Carbon – Steel Rebar before corrosion [14]

Concerning to Figure 2, ions are allowed to move into immersed electrolyte employing working electrode. Hence, it becomes enough to generate a big current by a potentiostat (in the way of potentiodynamically polarizing), thus indicating a low polarization resistance is a symbol of a high corrosion rate.

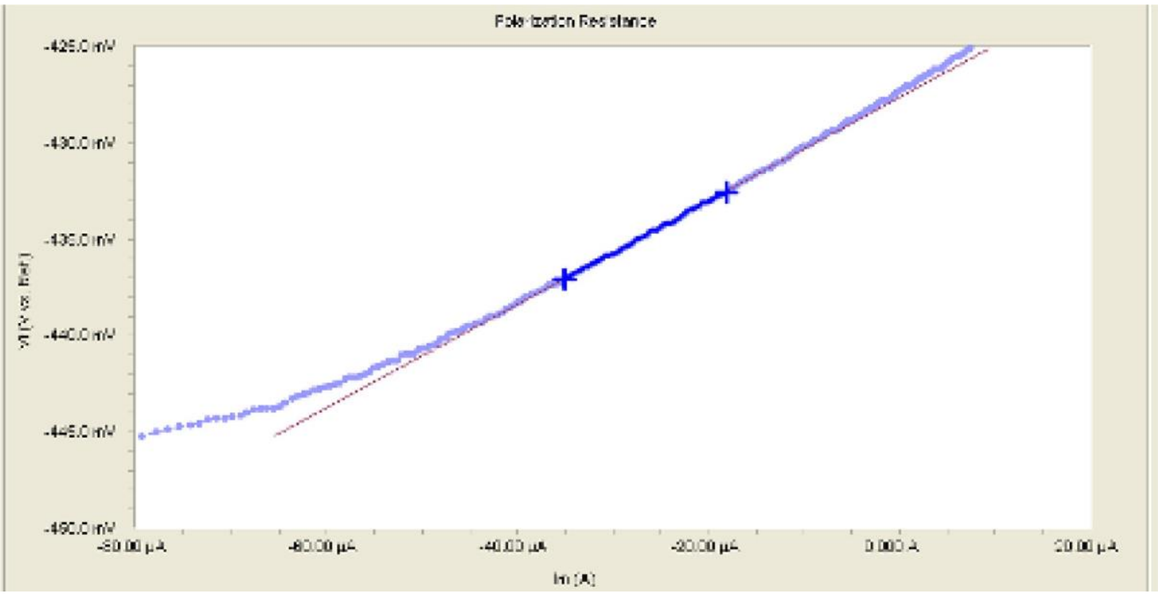


Figure 3. The diagram of Carbon – Steel Rebar after corrosion [14]

It can be noted that there is an extreme change in the range of -77.0mV to -425.0mV, which means severe corrosion is occurred.

1.4. Corrosion Rates (i_a)

The corrosion rate is defined as the quantity of corrosion that occurred at the surface area over a given length of time. This rate can be obtained by measuring the before and after weight of metals exposed to a corrosive environment. The general method of corrosion rate is the result of applying driving force (L) and anodic resistance (R). The driving force is the difference between Corrosion Potential (E_{corr}) and Equilibrium Potential (E_{eq}). Also, the driving force can be referred to as the forces pushing anodic reaction of corrosion equation and so, it is contrasted with the anodic resistance (R). Hence, formulation of corrosion rate is the ratio of L and R, which is $i_a = L/R$ formally. [21]

Corrosion rate also can be obtained by electrochemical methods. To be able to employ the electrochemical methods, Faraday's law can be used to turn electrochemical into gravimetric parameters.

$$\frac{I.t}{F} = \frac{\Delta W}{W_m/Z}$$

Where;

I = Electric current

t = Time

F = Constant value of Faraday (96500 coulombs)

ΔW = Weight difference of metal

Z = Valency of electrons

By this equation, current can be obtained which is also known as " corrosion density" or "Icorr" and this corrosion is assumed to be uniform corrosion in which will be referred to below at "corrosion types" part. That is allowed if there is a homogeneous attack and current obtained from the result must only be related with the surface exposed to the corrosion, hence it's written by $\mu A/cm^2$.

It must be noted that electrochemical methods are the methods that are difficult to apply due to the high value of the Faraday constant and also low rates of corrosion can be taken into account which is not reached with the same methods used in electrochemical ones.

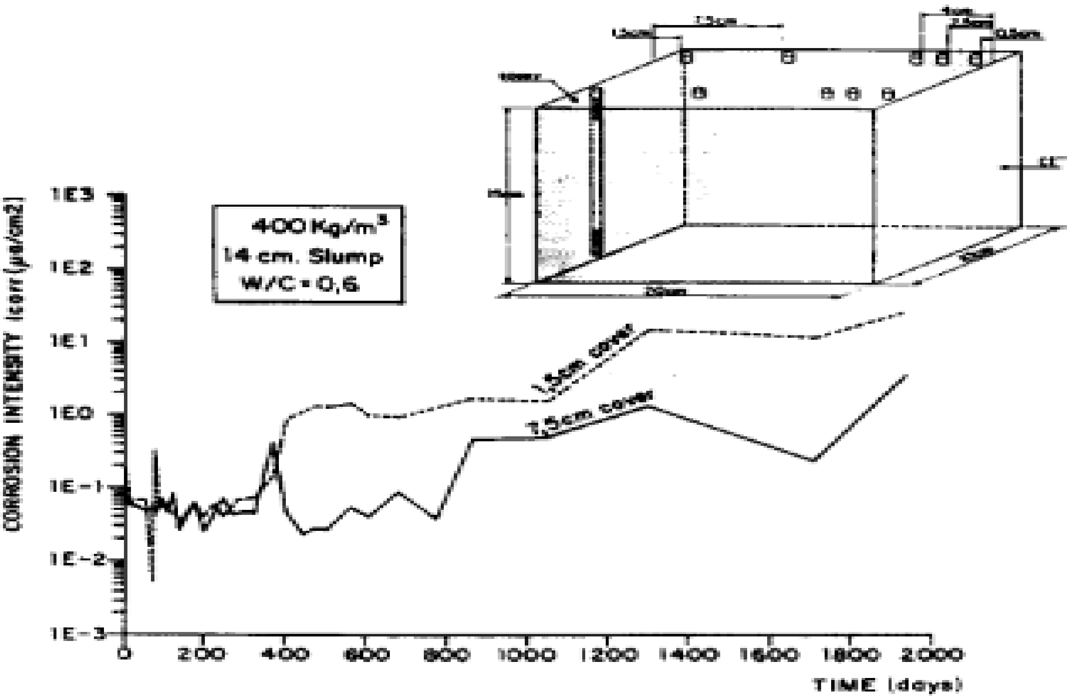


Figure 4. Structure behavior against seawater attack [14]

The corrosion density produces instant values while the method is used. When it is recorded on a regular basis and compared to a specific period in order to determine the evolution of the corrosion process, it is turned into corrosion rate. Despite the rate and density are the different parameters, they take into account the same purposes practically. Current values of corrosion density can be considered as a comparative factor between offshore structures. To give an example, Figure 4 showed above, refers to the act of a structure interacting with the seawater attack. The corrosion density is low at first, then increases extremely based on the behavior of steel.

There are many types of water and it is obvious that each has different quality in terms of corrosion. Offshore platforms, such as Oil and Gas Platforms are exposed to the most hazardous corrosion type coming from sea salt and immersion. Rates are driven by many factors. These are chemical factors, salinity, duration of wetness and temperature. As the ambient temperature increases corrosion rates increase as well. It was noted that a 10-degree difference in the weather affects corrosion 2.3 times faster due to more dissolution of the iron-carbon alloy. Concerning to chemical factors, it is noted that amount of chloride and sulfur dioxide increases while the system is corroding. The corrosion rates of metal artifacts exposed to the outside (bronze, copper, marble, and steel) are found to be proportional to the sulfur dioxide concentration. These types of factors are mostly based on the top part of the structure (Atmospheric zone) where the structure does not interact with the sea. The bottom part of the structure interacted with seawater has more corrosive media compared to the above part such as water velocity, pH and various dissolved salts coming from salinity. This complex form of marine environment makes the bottom part more significant and leads to all kinds of corrosion types.

1.5. Corrosion Types

There are different types of corrosion, which a metal can be affected in offshore platforms as well as zones that different types of corrosion may occur. These types can be listed as Uniform Corrosion, Galvanic Corrosion, Crevice Corrosion, Pitting Corrosion, Microbial Induced Corrosion.

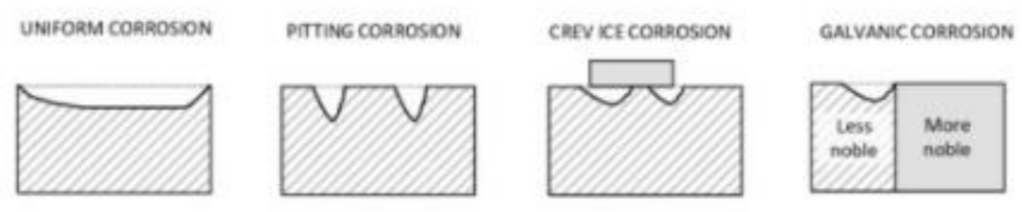
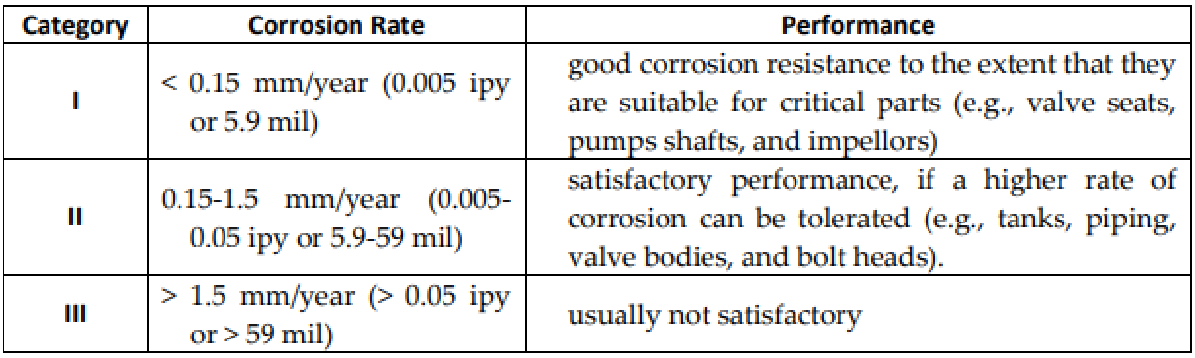


Figure 5. Types of Corrosion

1.5.1 Uniform Corrosion:

Uniform corrosion is also known as general corrosion. This corrosion is the consistent loss of metal over an entire surface. Although it is shown like the most dangerous corrosion type by its appearance, it’s quite easy to predict before it happens. Therefore, this corrosion is possibly the most well-known of all corrosion types by engineers. To get more comprehensive, engineers of NACE (National Association of Corrosion Engineers) have created a unit to be able to measure the corrosion rate (1 mil =0.001 in). Table 1 shows how the various rates of corrosion can be classified to correspond to the acceptable usage of materials.

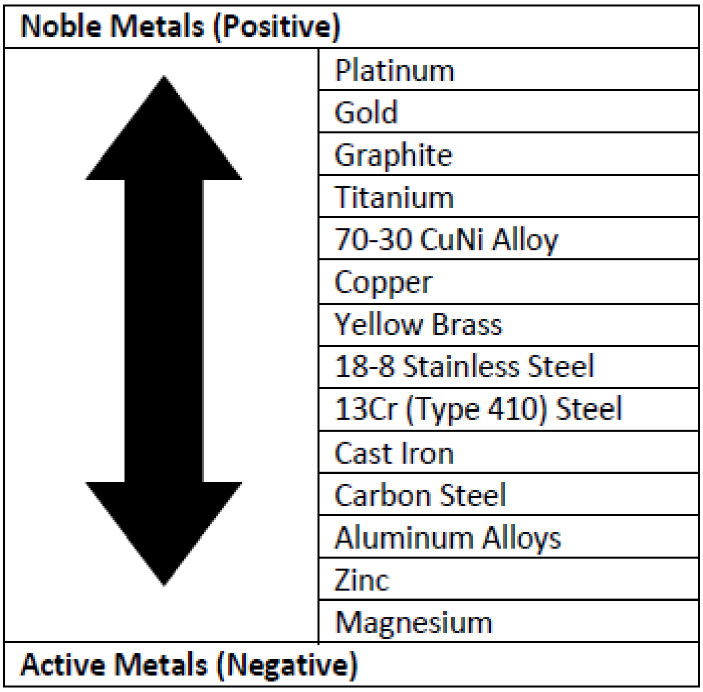


Category	Corrosion Rate	Performance
I	< 0.15 mm/year (0.005 ipy or 5.9 mil)	good corrosion resistance to the extent that they are suitable for critical parts (e.g., valve seats, pumps shafts, and impellors)
II	0.15-1.5 mm/year (0.005-0.05 ipy or 5.9-59 mil)	satisfactory performance, if a higher rate of corrosion can be tolerated (e.g., tanks, piping, valve bodies, and bolt heads).
III	> 1.5 mm/year (> 0.05 ipy or > 59 mil)	usually not satisfactory

Table 1. Classification of Corrosion Rate by its performance. [6]

1.5.2. Galvanic Corrosion:

Galvanic Corrosion is the most common corrosion process occurred in offshore platforms. The deterioration shows itself as a continuous layer of corrosion that covered the entire damaged surface area. When two dissimilar metals, such as stainless steel (SS) fitting and a regular carbon steel (CS) nut are electrically linked in the same electrolyte, galvanic corrosion occurs. Furthermore, galvanic corrosion can be detected by the electrical current defined earlier. As previously stated, metals having soiled components can form an electrical circuit in which electrons can move from one location on a metal surface to another, leading to corrosion. As a result, purified metals that contain positive potential compared to active metals have more resistance against corrosion and this difference in potential can be classified by Galvanic series. Table 2 shows the list of common metals regarding their potential.



Noble Metals (Positive)	
	Platinum
	Gold
	Graphite
	Titanium
	70-30 CuNi Alloy
	Copper
	Yellow Brass
	18-8 Stainless Steel
	13Cr (Type 410) Steel
	Cast Iron
	Carbon Steel
	Aluminum Alloys
	Zinc
	Magnesium
Active Metals (Negative)	

Table 2. Potential differences [6]

Noble metals are metals that can be used in their natural state after being recovered from the soil. Whereas, active metals require more energy to be able to use in a convenient form. This is a significant corrosion concept that is frequently encountered in the engineering field. To give an example, consider a positive metal such as platinum in which will be connected with a negative metal such as Magnesium. Electron reaction will start from negative metal (due to having higher energy) to active. As it can be seen in galvanic table above, negative metals tend to become more anode than positive metals. In this situation, magnesium is an anode whilst platinum is a cathode. The corrosion rate of the chemical reaction also depends on the distance between anode and cathode metals. In this case, platinum is too far away from magnesium, hence faster corrosion will be occurred. This rate also depends on the size of the surface area. When this ratio is combined with appropriate conditions, the rate of galvanic corrosion between two metals can be determined. For example, the rate of small anodes against large cathodes will be higher. Hence, corrosion is considered minimal until the anode area exceeds the cathode area. As a result, a small ratio of anode/cathode will cause more deterioration of the anode, therefore small places are being affected by this corrosion such as sharp points and edges of structures. [6]

1.5.3. Crevice Corrosion

This corrosion is also popular in offshore platforms. It’s more likely to happen in the offshore environment including small amounts of stagnant chloride-rich fluid existing at joints between metallic surfaces. Corrosion is getting bigger at the joint due to a potential difference on the metal surface, contrasting surroundings in contact with the crevice at depth, and more oxygen surrounded at the outer surface. A crevice must be wide enough to allow the corrodent to enter but narrow enough to keep the corrodent stationery in order to act as a corrosion site. As a result, crevice corrosion occurs in gaps a few micrometers length and is not seen in grooves or slots where the corrodent can circulate. Resistance of the stainless steel depends on oxid coating covered on the surface, however, this coating can break down under specific conditions fluoride or chloride solution. In addition, the design of the other components can cause the breakdown of the oxid coating. For instance, overlapping surfaces or under gaskets can be the way of breakdown. Crevice corrosion is also one of the localized corrosion types such as pitting or fretting corrosion. When compared to pitting corrosion, crevice corrosion is a less strict kind of localized corrosion. Pitting corrosion has a substantially larger penetration depth and rate of propagation than crevice corrosion. Value of pH inside to conceive may drop to 2 in a neutral condition and also creates a deeply acidic environment where most of the metals can be corroded. [8]

Two factors play a role in the onset of crevice corrosion for a specific crevice type; the chemical combination of the electrolytes located in the crevice and potential drop. According to previous research, either of them leads to start the crevice corrosion however it was claimed that active crevice corrosion is caused by a mixture of both. Both of these factors are the result of deoxygenation and potential difference of electroactive areas where anodic reactions appear into the crevice and cathodic reactions appear out of the crevice. [7]

Crevices can produce local chemistry that differs significantly from the bulk fluid's. Because of the continual vaporization of water in boilers, non-volatile contaminants may accumulate in fissures near heat-transfer surfaces. For typical water contaminants like salt, sulfate, or chloride, "concentration factors" in the millions are not unusual. This process is also known as “hideout”.

1.5.4. Pitting Corrosion

This is the other type of localized attack that results in the formation of a pit and metal perforation. It is one of the most hazardous types of corrosion because it causes a part to degrade without causing significant weight loss. Pitting takes a longer time to develop before being noticeable also would be difficult to detect its depth. When it started, a pit, on the other hand, continues to connect the area at an ever-increasing rate. Pitting can be occurred by a stagnant liquid in a tank or the lowest part of a pipe. Like the other corrosion types, the majority of pitting is caused by halide ions, the most common of which are chlorides, bromides, and hypochlorites. Pitting can be accelerated by oxidizing metal ions with chlorides. The most significant approach to preventing this problem is to use a more resistant material against pitting corrosion. For instance, type 316 stainless steel could be an efficient way of preventing pitting corrosion compared to type 304. To be clear, stainless steel with higher grades is better suited for offshore platforms. On the other hand, it is obvious that stainless steel is a better material selection for saltwater projects than carbon steel or aluminum due to production of chromium. The other alloying elements can be Mo, Ti, W or N. These elements, especially Mo, can considerably increase Chromium enrichment in the oxide, which cures or repassivates the pit. Chromium is important to classify the rate of pitting by using in

Pitting resistance equivalent number (PREN) in which an expiremental approach to estimate the pitting resistance of metal. It can be shown as follows;

$$PREN = Cr + 3.3\ (Mo + 0.5\ W) + 16N. \tag{1.5.4.1.}$$

According to ASTM Standard G48-03, In order to evaluate the resistance of an alloy against pitting corrosion, critical pitting temperature (CPT) can be used. The critical pitting temperature (CPT) is the lowest temperature (in degrees Celsius) at which pitting corrosion can occur, and it is usually greater than the critical crevice temperature (CPT).

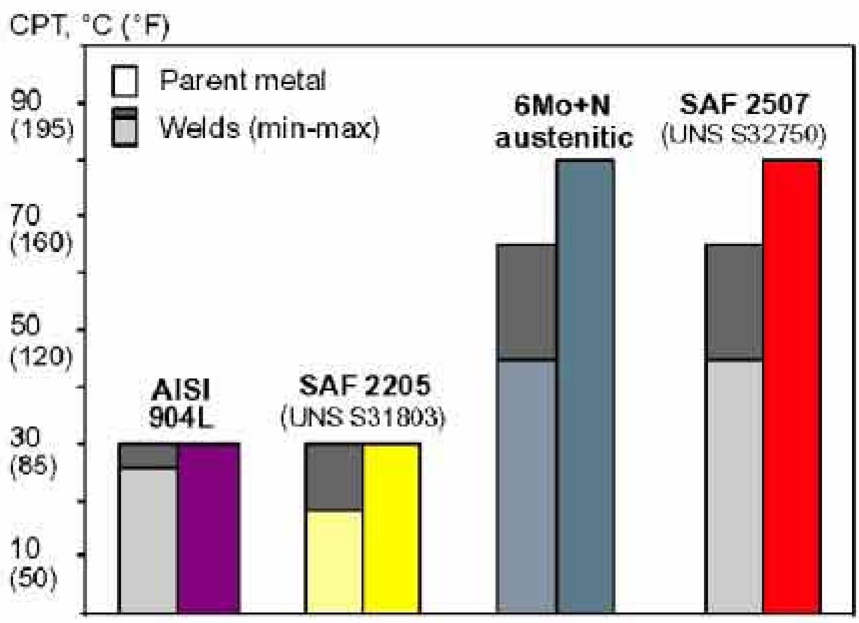


Figure 6. Materials's resistance to pitting corrosion according to ASTM Standart [55]

Concerning to shapes of pitting, pitting corrosion can take different forms. In general, it can be separated as Through and Sideway Pitting Corrosion. Through, pit shape tends to be wide and elliptical, narrow and deep or shallow and wide. Whereas, Sideway Pitting tends to be horizontal, subsurface or undercutting as follows.

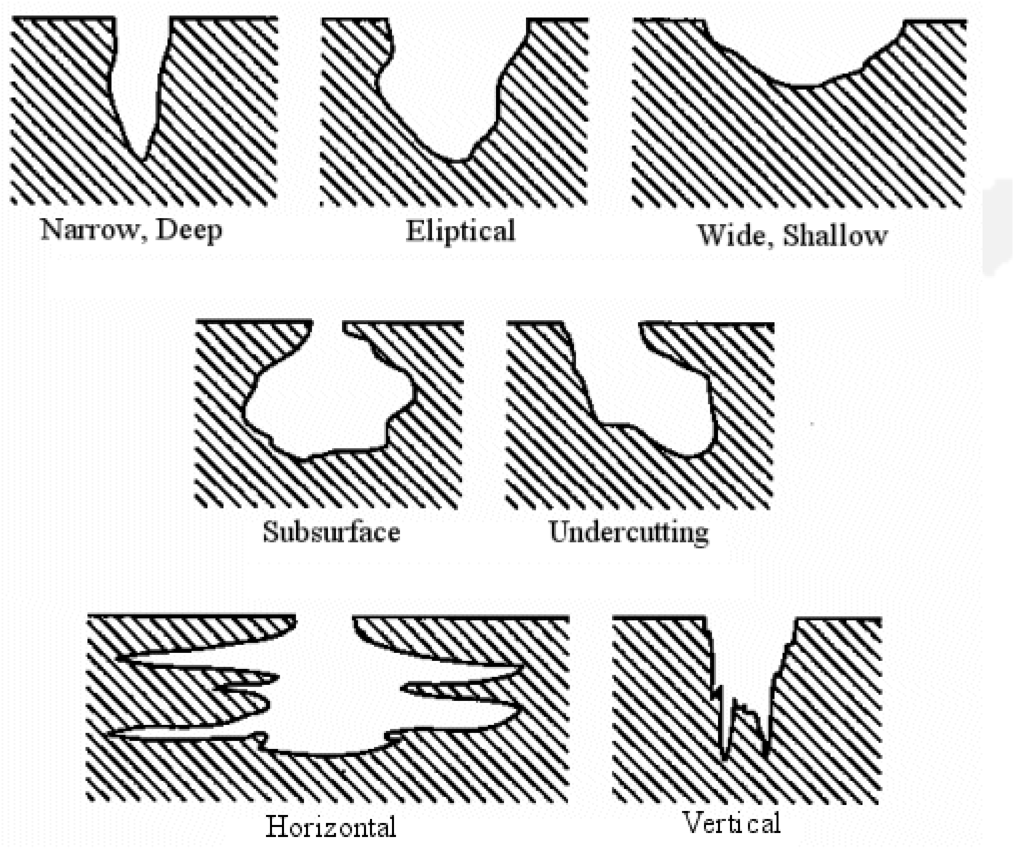


Figure 7. Standart visuals of pitting corrosion [55]

Pitting corrosion's shape can only be determined by metallography, which involves cutting a pitted sample in half and determining the pit shape, pit size, and pit depth of penetration.

1.5.5. Microbial Induced Corrosion

This corrosion is more likely to occur in tropical seas where different microorganisms and bacteria are surrounded. The bacteria produce a variety of by-products once the biofilm expands, including organic acids, hydrogen sulfide (H2S), and slime. Acids and a bacterial environment that has been altered cause pitting.

Scientists are familiar with the corrosion types referred to above; but, if there is corrosion caused by microbial induced they are probably not. There is two type of biological reaction between metal and the environment. The first type is called passive attack, and it happens when biological materials are chemically inactive and act like any other deposit accumulation, providing protected zones beneath which electrochemical corrosion cells can form. The second type is an active attack, which occurs when microbes' metabolic activity directly causes corrosion. The main reason for this corrosion is a metallic waste when bacteria cause chemical reactions at the cathode or anode part of the metal. The bacteria may produce cathodic depolarization by eliminating hydrogen deposited on metal surfaces, according to one theory. Concerning to steel pipelines, there are many types of bacterias causing corrosion. Sulfate Reducing Bacterium is a well-known form of bacteria that is typically found in cold water environments (SRB). Sulfate-reducing bacteria does not only interact with steel, it can also interact with aluminum in unexpected areas. The bacteria hibernates in oxygenated water and dies when exposed to air. It has been shown in studies that it can survive in harsh environments where other bacterias can not. It can survive in 5 to 9 pH which means surviving all over the offshore environment.

On the other hand, the SRB would always strive to protect themselves from the oxygenated water beneath dome formations known as tubercles on the metal substrate. Low places inside pipework systems, edges where water can gather, and shut-in piping are hence preferred locations for its growth. Other convenient places for its growth can be tank bottoms or areas including surface deposits.

It's not easy to determine a biological factor in a corrosion process. Determination is hence upon environmental factors, damage analysis and the corrosion product. Striations and tunneling into the side of the corrosion pit are other common aspects, As it seen in Figure 4. Corrosion pits are usually made of multiple smaller pits with hemispherical and wide shapes; striations and reaching into the side of the corrosion pit are other common features.

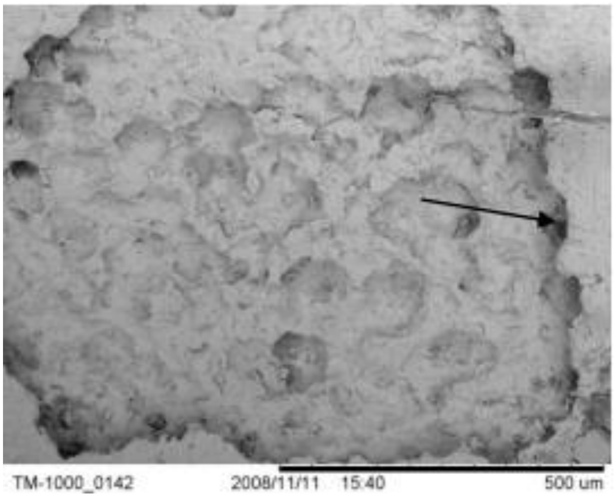


Figure 8.1. SEM images of several pits trying to reach out the edge of the corrosion pits [56].

If SRB is not detected and treated, it might induce pinhole formation due to rapid localized pitting corrosion.

1.5.6. Environmental Cracking

Environmentally induced cracking in metals and alloys indicates fragile mechanical failure. Because of the synergy between tensile stress and corrosive environment, it occurs in vulnerable metals or alloys. The main reason for the Environmental cracking corrosion is tensile stress, as well as corrosive environment surrounded the place has a significant role. Because of the corrosive environment, tensile stress, which is significantly lower than the yield stress, is active in causing cracking in metals and alloys. In environmentally generated cracking, the corrosion rate is generally modest. However, environmental-induced cracking can cause serious deterioration of metals or alloys because it can trigger the onset of other harmful processes.

There are three types of Environmental Cracking corrosion. These are determined as hydrogen-induced cracking(HIC), stress corrosion cracking (SCC) and liquid metal embrittlement (LME). [10] Stress Corrosion Cracking is a well-known type of Environmental induced corrosion in which type of time-dependent environmental induced cracking that occurs more frequently in alloys as an anodic process. As the stress ratio increases at corrosion place, SCC occurs. Despite most parts of the metal and alloys do not interact with SCC, several fine fractures spread slowly over the surface of the alloy composition. SCC's cracking surface resembles a separation when there are no corrosion products present. Figure 5 shows the common examples of SCC; season cracking and caustic embrittlement.

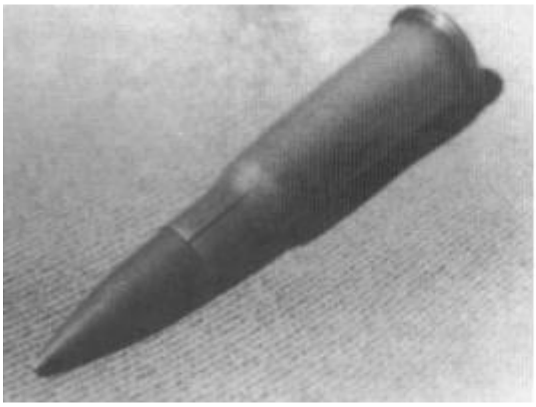


Fig 8.2. Example of season cracking [10]

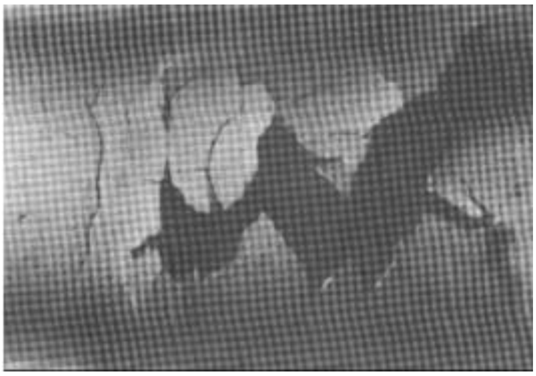


Fig 8.3. Example of “Caustic embrittlement” in a stainless steel [10]

There are three conditions significant for Stress Corrosion Cracking. These are tensile stress, corrosive environment and susceptible alloy. [10] The most important condition is tensile stress. The impact of tensile stress on SCC is highly dependent on the type and intensity of the stress. Furthermore, tensile stress must interact with alloy in a corrosive environment. If chemical component, aqueous solution, suitable temperature and moisture are surrounded by susceptible alloy, a corrosive environment can be generated. The susceptibility of alloys is also a necessary factor for SCC to take place. The susceptibility of an alloy is highly dependent on its strength and grain orientation, bulk alloy chemistry, alloy microchemistry, and surrounding, as well as the severity of the environment and loading factors. Also pH, the sensitivity of the passive film, the intensity of stress and electrochemical potential are effective factors for alloy susceptibility. Figure 9 shows the three conditions of SCC.

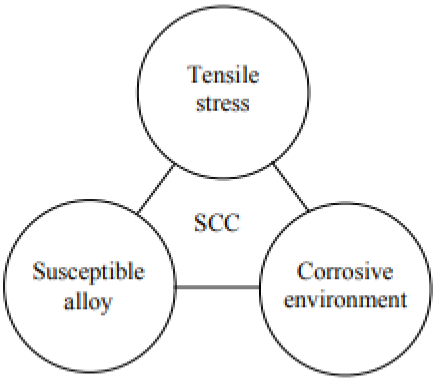


Figure 9. Conditions for the existence of Stress Corrosion Cracking. [10]

1.6. OFFSHORE CORROSION AREAS

As the platforms are installed in the offshore environment, some parts of the structure will be submerged and some parts will be above sea level. On the other hand, the boundary part between the submerged and above part of the construction will be in a zone where they will be in and out of seawater on a regular basis, owing to varying water levels caused by tidal movement. These areas can be classified separately and requirements must be known properly before Cathodic Design. These three-part can be classified as Athmosperic Zone, Splash Zone ad Submerged Zone.

1.6.1. Atmospheric Zone

The atmospheric zone is the above part of the structure and this part is neither wetted nor impacted by the ascent of tidal waves. As it’s not interacted with the sea, this zone does not include electrolytes. To be able to prevent corrosion, a convenient coating can be considered. In other words, as an electrolyte does not interact with this zone cathodic design is not required. The structure's design aims to keep the exposed steel surface area in this zone to a minimum. To be able to minimize the exposed steel surface can be done by tubular members. Clean welds having good profiles that merge into the parent metal prevent any crevice type corrosions, and steel structures can be boxed in to achieve the same aim. Another way of building a structure with a reduced potential to corrode is replacing steel with corrosion-resistant materials and nonmetals whenever available. It should be noted that dissimilar metals are to be joined is not recommended while designing, however, providing a solution between joints can be a convenient way. This method eliminates the risk of damaging design features that tend to corrosion by their nature.

1.6.2. Splash Zone

The area of an offshore structure that is periodically in and out of water owing to the impact of waves or tides is known as the splash zone. Waves, wind and daily tidal variations can an cause increase in corrosion on exposed metal surfaces by alternating soaking and drying. The height of the splash zone can be considered as the vertical distance between the upper part and lower part based on its high and low tide. According to Det Norske Veritas, the astronomical tidal range plus a wave height with a 0.01 chance of exceeding it. The top limit of the splash zone is calculated by assuming that 65 percent of the wave height is above the highest astronomical tide (HAT), and the lower limit is calculated by assuming that 35 percent of the wave height is below the lowest astronomical tide (LAT). [11]

Splash zone can be considered as the parts such as pipeline field joints and riser systems. As the sea level varies constantly, cathodic protection is not a convenient way of preventing corrosion for this place. Cathodic protection is used for the parts that are fully submerged. Paints and zinc coatings can be used to protect portions above the "splash zone" that are solely exposed to the atmosphere, but they must be reapplied as needed. Also, Thermal Sprayed Aluminum coating is widely specified for the protection of the splash zone. To be able to provide sufficient prevention metal must be isolated by coating and some materials can be suitable such as rubber or polyurethane. Also, the coating is to be designed must avoid the structure from electrolytic corrosion. The other requirements can be listed as having good thermal isolation, flexibility, impact resistance and bio-fouling resistant.

1.6.3. Submerged Zone

The submerged zone is the part that is located completed into the seawater and below the splash zone. As the interaction between electrolyte environments, cathodic protection can be considered. To be able to protect this part, a well-designed cathodic design and high-performance coating system can be combined. As it does in the atmospheric zone, in order to reduce the risk of corrosion at the tight corners and crevices which are difficult to cover by using coating, tubular structures are preferable. From the design stress-reduction point of view, fatigue stress should be decreased and if necessary, the design should also relieve the tension exerted on welded members.

All kinds of piles such as structure and skirt piles, as well as centralizers, must be considered to be a part of the Cathodic Protection system while designing. These members are welded to the jacket legs in order to connect, and their whole surface area must be taken into account while calculating the total polarization amount. The rest of the part must be welded conveniently in order to bound electrically through the structure to provide cathodic protection. The structures that are not welded can be taken into account as one structure with the rest of the structure after electrical bonding for calculating polarization current and determining anode mass and amount.

Even if they are in the submerged zone, the part of the submerged system that closes to mudline has a very low corrosion rate compared to the above part due to the fact that non-oxygen environment or the turbulence interacted with steel, however, these parts must be included in the whole Cathodic Protection system as well. Concerning to chain members, chains are structural elements that span the splash and submerged zones, and they are frequently designed with double the corrosion allowance as the rate of corrosion. As explained in Splash Zone, Cathodic Protection is not a well-protected system for the splash part, whereas this part must include a high corrosion allowance. Hence, engineers should make every effort to maintain the chain's lie inside the effective radius range of the Cathodic Protection current, offering some protection to the chains.

The protection of galvanized steel is not as same as chains, and its wire ropes are protected from water by a polyurethane coating loaded with grease on the outside. The galvanized wires are sufficiently protected from corrosion by this wrapping. A good wire rope design, on the other hand, will contain a sacrificial zinc wire as secondary protection within the rope composition.

1.7. Materials and Corrosion Behaviour of Materials

Due to the risk of the offshore environment, materials used for the structures should be selected carefully. Although the accidents recorded in the oil and gas industry is not critically high, materials degradation could lead to a costly and dangerous situation with serious consequences for human life and the environment. Crystal structures of the materials are distinct features for each material which can be described by its unite cell. This cell consists of a body in which atoms are set up. There are three types of body that is observed in general; the body-centered cubic, face-centered cubic and hexagonal-close packed cubic.

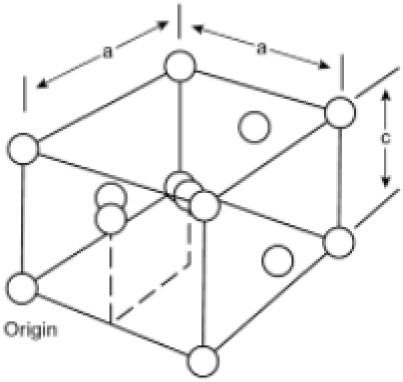


Figure 10.1 Body-Centered Cubic

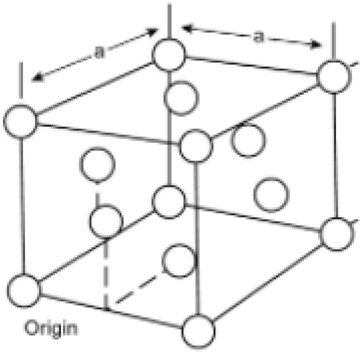


Figure 10.2 Face-Centered Cubic

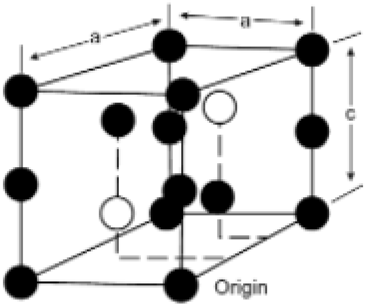


Figure 10.3 Hexagonal – Close Packed Cubic

Although structure crystals of each metal are presented in the same condition, some of them can be changed based on their environment. For instance, titanium has a Hexagonal – Close Packed Cubic form in general but its structure crystal can be oriented as Body – Centered Cubic form in the environment where the temperature is higher than room temperature. This situation is called allotropes. Structure crystals of metals are bonded to each other in different ways, called grains, and this connection of grains are known as grain boundaries. The acting of the metals against corrosion is highly related to these grain boundaries and a high amount of grain boundary decreases the corrosion resistance of a metal. In order to increase corrosion resistance, other elements can be oriented with pure metals and this interactionis called alloy solution. Before metal and its alloys are decided, their structure crystals, mechanical features and phase diagram should be investigated. Metals can be classified as it can be seen below in Table.3

Body-Centered Cubic	Chromium, iron, vanadium, molybdenum
Face-Centered Cubic	Silver, aluminum, copper, gold, nickel
Hexagonal–Close Packed Cubic	Titanium, zinc, magnesium, cobalt

Table 3. Classification of metals in terms of Structure Crystal Form

Some of the metals shown above are suitable for the offshore environment but the addition of alloy may be required for resistance. These are also not only suitable for up-stream, mid and down-stream. Most common materials can be listed as Stainless Steel, Carbon Steel, Cast irons and Alloy steel, Also Copper Alloys, Nickel Alloys and Titanium Alloys are known as corrosion-resistant alloys (CRA). CRAs are generally applied for the places where the corrosion rate is high.

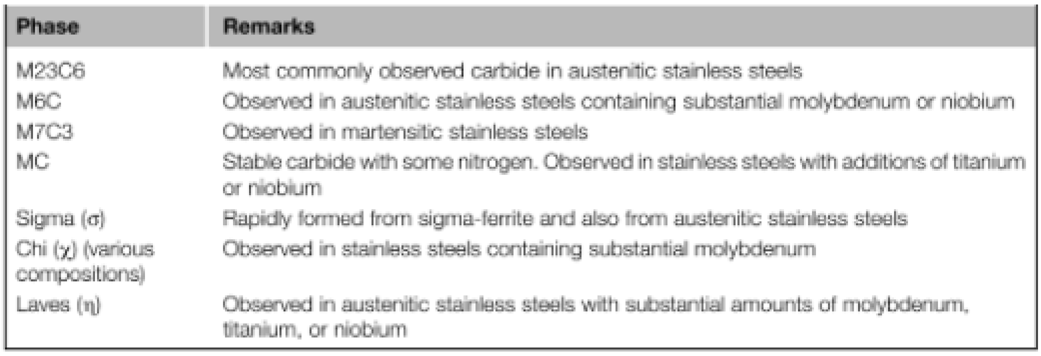
1.7.1. Stainless Steel

As it can be noted by its name, stainless steel is a combination of 2 metals in order to provide more resistance. The first metal of stainless steel is iron, exposed to corrosion when its interacted with seawater. In order to provide corrosion resistance, chromium is added as second metal. Although stainless steel has built-in corrosion resistance, it can and will be corroded under certain conditions. The rate of its corrosion resistance depends on the amount of chromium present.

The minimum limit amount of chromium that should be added to iron is 10.5 percent. Also, nickel and molybdenum can be introduced into it to increase mechanical resistance. This chromium interacts fast with the oxygen in the air, forming a thin oxide coating on the surface of the steel. As a result, it serves as a protective barrier. The chromium oxide acts as a passive coating, keeping the iron in the alloy safe from the environment's air and water. Thus corrosion resistance of stainless is provided.

High maintenance is not required for stainless steel and it’s one of the most common materials around the offshore industry due to its low maintenance and resistance to oxidation.

Austenitic, ferritic, martensitic, and duplex stainless steels are the four main varieties of stainless steel. Austenitic stainless steel is the most common in the industry, accounting for more than 70% of total stainless steel production. It includes maximum of 0.15% carbon and at least 16% chromium which makes it very strong against corrosion. Based on their strength, ferritic can be listed as second, rather than martensitic. Also, concerning to pitting or localized corrosion, duplex stainless steel can be selected to achieve high corrosion resistance. Apart from these varieties, there are also some components that may be observed. (Table 4) [16]



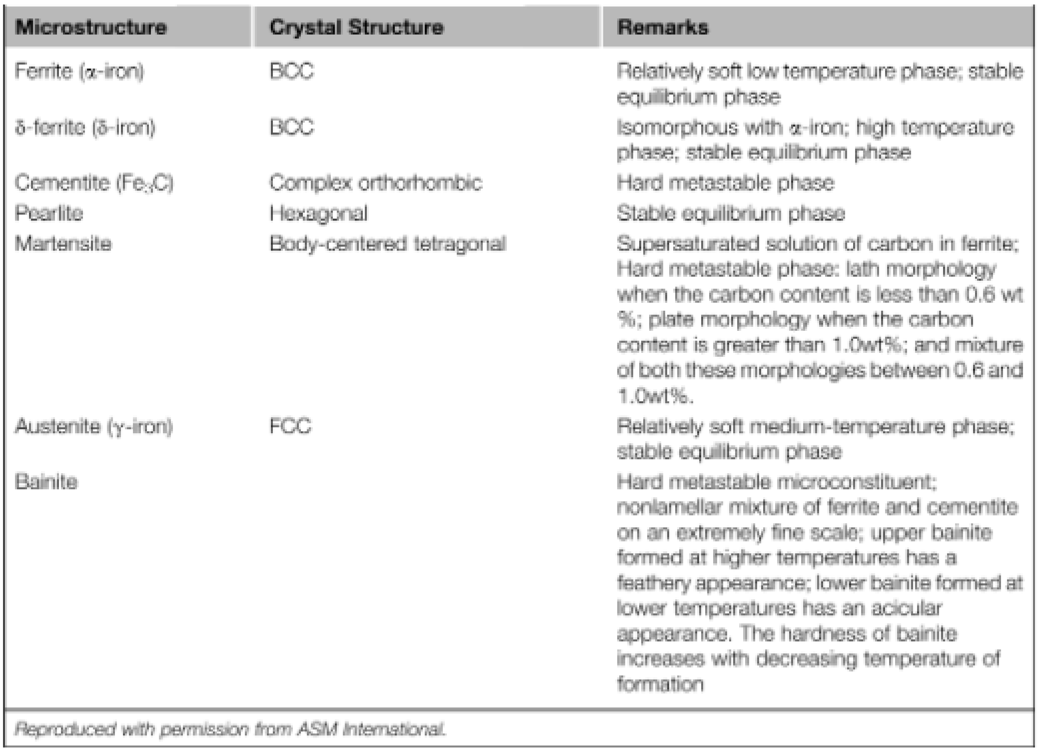
Phase	Remarks
M23C6	Most commonly observed carbide in austenitic stainless steels
M6C	Observed in austenitic stainless steels containing substantial molybdenum or niobium
M7C3	Observed in martensitic stainless steels
MC	Stable carbide with some nitrogen. Observed in stainless steels with additions of titanium or niobium
Sigma (σ)	Rapidly formed from sigma-ferrite and also from austenitic stainless steels
Chi (χ) (various compositions)	Observed in stainless steels containing substantial molybdenum
Laves (η)	Observed in austenitic stainless steels with substantial amounts of molybdenum, titanium, or niobium

Table 4.Other components in Stainless Stells [16]

1.7.2. Carbon Steel

Carbon Steel is also frequently used in Offshore Industry, especially in Oil and Gas Industry, because of its availability, convenience and low price. However, as structure are not well protected because of its inefficient corrosion resistance, there is a limit of applying Carbon steel. For more information, its basically suitable for the corrosion where happens in pipe due to producing oil and gas, but by the addition of sand corrosion, resistance can not be efficient. [17]

The main metal of carbon steel is also iron and concerning to crystal structure, iron is a Body-Centered Cubic. The amount of carbon added to iron is 2.5%. In order to provide efficient resistance, some components can be selected based on the phase of the corrosive area. These are Ferrite, Cementite, Pearlite, Martensite, Austenite and Bainite. The most common carbon steel is Ferrite. As Ferrite is easy to deform due to its low amount of carbon, some other alloys can be added such as silicon. Cementite and Martensite are preferable for hard steel such as dual-phase steel, therefore not preferable for low carbon steels. Pearlite and Bainite are combinations of ferrite and cementite but generally, Pearlite is desirable. And finally, austenite is not suitable with every steel but low carbon steels and dual-phase steels. For more information on the type of Carbon Steel, Table 4 is shown below.



Microstructure	Crystal Structure	Remarks
Ferrite (α-iron)	BCC	Relatively soft low temperature phase; stable equilibrium phase
δ-ferrite (δ-iron)	BCC	Isomorphous with α-iron; high temperature phase; stable equilibrium phase
Cementite (Fe_3C)	Complex orthorhombic	Hard metastable phase
Pearlite	Hexagonal	Stable equilibrium phase
Martensite	Body-centered tetragonal	Supersaturated solution of carbon in ferrite; Hard metastable phase: lath morphology when the carbon content is less than 0.6 wt %; plate morphology when the carbon content is greater than 1.0wt%; and mixture of both these morphologies between 0.6 and 1.0wt%.
Austenite (γ-iron)	FCC	Relatively soft medium-temperature phase; stable equilibrium phase
Bainite		Hard metastable microconstituent; nonlamellar mixture of ferrite and cementite on an extremely fine scale; upper bainite formed at higher temperatures has a feathery appearance; lower bainite formed at lower temperatures has an acicular appearance. The hardness of bainite increases with decreasing temperature of formation

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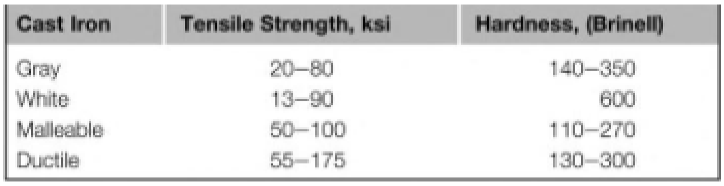
Table 5. Types of Carbon Steel [16]

1.7.3. Cast Irons

Cast iron is the combination of iron, silicon and carbon alloys with greater than 2% carbon content [18]. As cast irons are highly fluid, its commonly useable to unite the materials. Based on tensile stress and hardness, it can be classified into malleable, gray, ductile and white. If Cast Iron contains a sufficient amount of alloy, corrosion resistance can be as much as Stainless Steel has. Silicon, copper, nickel or molybdenum can be added in order to provide this corrosion resistance.



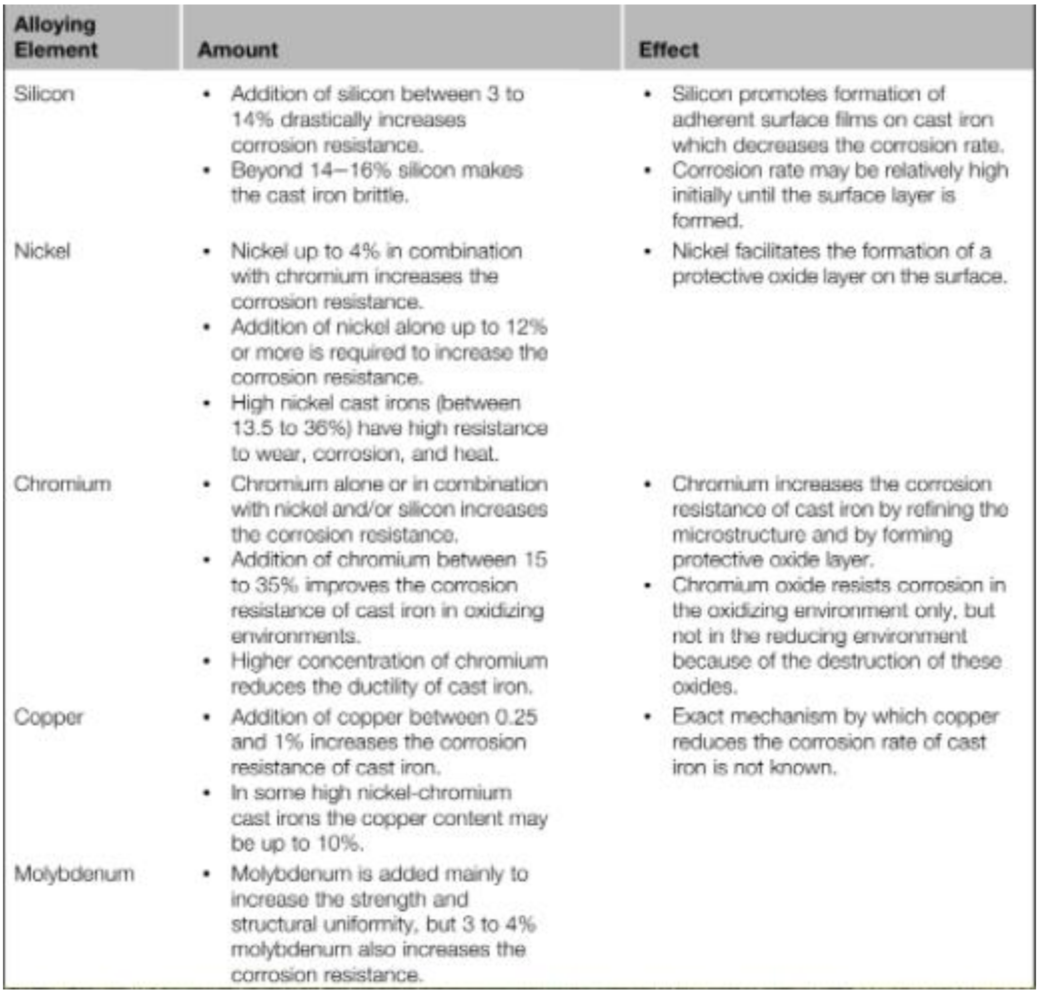
Cast Iron	Tensile Strength, ksi	Hardness, (Brinell)
Gray	20–80	140–350
White	13–90	600
Malleable	50–100	110–270
Ductile	55–175	130–300

Table 6. Types of Cast Irons [16]

1.7.4. Alloy Steels

Alloy steels is the steels that interacted with some elements in order to increase the mechanical features, such as corrosion resistance, hardenability and strength. The amount of these alloys can be changed between 1% to 50% in accordance with steel's requirement. Based on this requirement, alloys steel can be defined into two groups; low alloy and high alloy steels. In the offshore industry, alloy steels are defined as low alloy steels. According to Smith and Hashemi, the low alloy limit is 4%, on the other hand, Degarmo defines it as 8%. [19]

Previous materials defined above also include alloy materials but it should not be considered that those are also alloy steels. In order to be defined as alloy steel, steel should be alloyed with molybdenum, silicon, chromium, nickel, boron and vanadium. The most common alloying elements and their effects on steel are shown in Table 6. [16]



Alloying Element	**Amount**	**Effect**
Silicon	• Addition of silicon between 3 to 14% drastically increases corrosion resistance. • Beyond 14—16% silicon makes the cast iron brittle.	• Silicon promotes formation of adherent surface films on cast iron which decreases the corrosion rate. • Corrosion rate may be relatively high initially until the surface layer is formed.
Nickel	• Nickel up to 4% in combination with chromium increases the corrosion resistance. • Addition of nickel alone up to 12% or more is required to increase the corrosion resistance. • High nickel cast irons (between 13.5 to 36%) have high resistance to wear, corrosion, and heat.	• Nickel facilitates the formation of a protective oxide layer on the surface.
Chromium	• Chromium alone or in combination with nickel and/or silicon increases the corrosion resistance. • Addition of chromium between 15 to 35% improves the corrosion resistance of cast iron in oxidizing environments. • Higher concentration of chromium reduces the ductility of cast iron.	• Chromium increases the corrosion resistance of cast iron by refining the microstructure and by forming protective oxide layer. • Chromium oxide resists corrosion in the oxidizing environment only, but not in the reducing environment because of the destruction of these oxides.
Copper	• Addition of copper between 0.25 and 1% increases the corrosion resistance of cast iron. • In some high nickel-chromium cast irons the copper content may be up to 10%.	• Exact mechanism by which copper reduces the corrosion rate of cast iron is not known.
Molybdenum	• Molybdenum is added mainly to increase the strength and structural uniformity, but 3 to 4% molybdenum also increases the corrosion resistance.	

Table 7. Alloying Elements and Their Effects [16]

Chapter 2

CATHODIC PROTECTION

2.1. Principle of Cathodic Protection

Corrosion was implied at the previous sections as a reactions consisting of two sides in which electrons are gathered in cathodic side and given off in anodic side. Before referring to Cathodic Protection, cathodic and anodic side of corrosion must be defined in detail. To begin with, a interaction between iron and aqueous environment leads to a reaction. As a result of this chemical or electrochemical reaction between iron and aqueous environment, equation 4.1. occurs.

$$2Fe + O_2 + H_2O \rightarrow 2Fe(OH)_2$$

(4.1.)

Due to oxidation, this output ($2Fe(OH)_2$) then turns into magnetite (Fe_3O_4) or FeOOH (hydrated ferric oxide), which means it's corroded.

This is the general corrosion reaction of iron which leads to an electron transfer process that is a charged metal ion is formed while an uncharged metal atom loses electrons as shown separately in Equation 4.2. and 4.3.

$$2Fe \rightarrow 2Fe^{2+} + 4e^-$$

(4.2.)

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

(4.3.)

Positively charged ferrous ions have a tendency to dissolve in electrolyte solutions, thus electron gathers at the end of the metal as the result of a certain electric potential difference. As a result, an oxidation reaction occurs which is also known as an anodic reaction as Equation 4.2. and this end place of the metal is the anodic area.

In addition, electrons interact with hydrogen ions and hence, hydrogen is formed as it can be seen in Equation 4.3. This is known as cathodic reaction and this end place of the solution is the cathodic area.

As a result, electrons that occurred in the anodic reaction[2] are employed in the cathodic reaction[3] and there is no deficiency in terms of electrons availability (If both cathodic and anodic sides work similarly). Thus metal becomes its electrode potential, which is also known as corrosion potential (E_{corr}). Figure 8 shows the relationship between anodic and cathodic reactions and how the electrons released from the anodic reaction are consumed in a cathodic reaction.

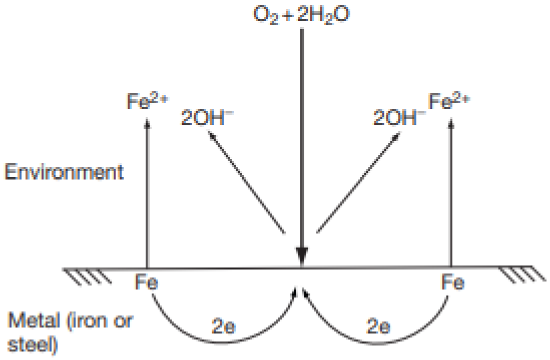


Figure 11. Basic corrosion process that electrons released in Anodic Reaction are taken by Cathodic Reaction and leads to a metal consumption. [20]

It can be easily noted what might happen if this reaction happens in terms of the anodic side and cathodic side. For more information, as electrons are taken from the metallic surface, it can be expected that Equation 4.2. would be faster in order to change the lost electrons. Whereas, Equation 4.3. would be slower due to the deficiency of electrons. As a result amount of metal consumption would be higher.

Hence, in order to keep electrons on a metallic surface, additional electrons should be used and thus, the anodic reaction can be controlled. As anodic reactions are being controlled, the cathodic reaction will be higher in order to consume the electrons. As a result metal consumption would be slower. This technique is known as Cathodic Protection. Figure 8 shows the consumption of additional electrons rather than the electrons released from an anodic reaction. By this solution, the cathodic reaction would be able to get its required electron (2 electrons) without using an anodic reaction in order to achieve its partial cathodic protection. Also, it can be noted in Figure 9 that by getting 2 electrons from the external source, one of the anodic reactions that occurred in Figure 8 is prevented.

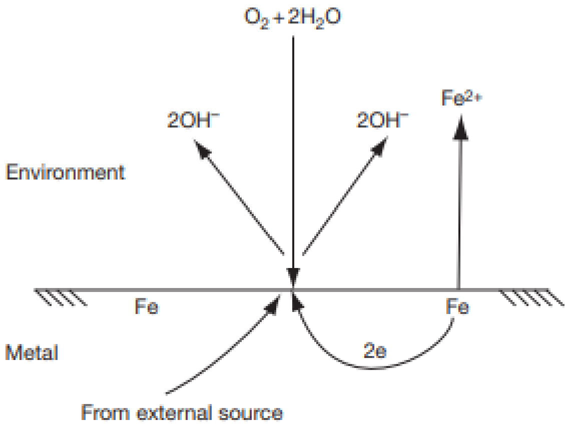


Figure 12. Partial Cathodic Protection in which 2 electrons are taken from an external source rather than iron atoms.[20]

As a result, in order to achieve full cathodic protection, the surface should be purified from OH^{-}which means 4 electrons released from external source is required. Figure 10 shows the fully protected surface where the accumulation of OH^{-} does not exist due to control of anodic reaction.

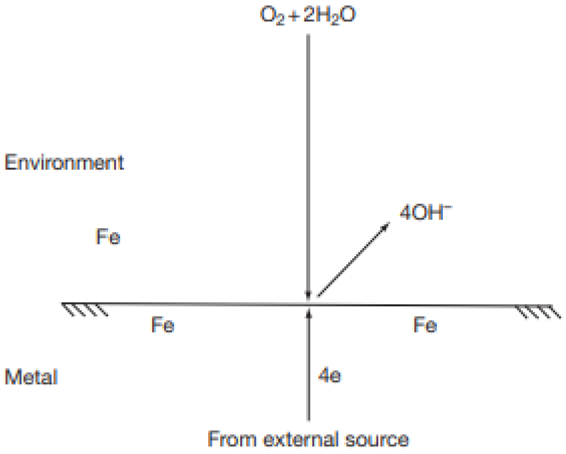


Figure 13. Fully protected metallic surface by cathodic protection [20]

When an immersed metal and solution starts interacting, there will be a phase where the energy of the ion is larger through smaller from either direction. However, only the cations with charged positively will be able to pass into the solution, which means negatively charged anions can not pass. Hence, there will be an accumulation of positive ions. Equilibrium is the phase when chemical driving force (L) equals the electrical force of the reaction and the potential differences between metal and the solution is known as “equilibrium potential difference”. [22]

According to the change of behavior of metal, active, passive, ineffective and hydrogen evolution part can take place during the process. Figure 11.1. and 11.2. show the active and passive behavior of metal and its hydrogen evolution.

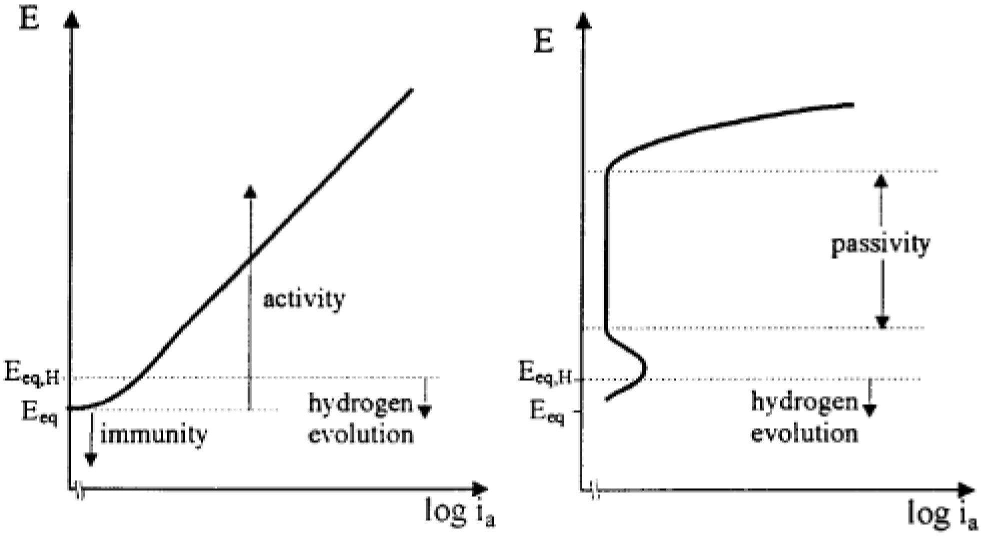


Figure 14.1. “Active” , 14.2. “active-passive”[23]

2.1.1. Positive Effects of Using Cathodic Protection

The electrolyte interaction of cathodic and anodic structure are mostly related with the change of the cathodic structure’s potential in the negative way and this negative way can lead to two beneficial result in terms of the system; decreasing the driving force (L) and increasing the anodic resistance (R) kinetically.

When Cathodic Protection is reached out the structure’s potential to zero point or any point that is less than E_{eq}, the corrosion rate of the structure will be smaller due to the fact that driving force becomes lower.

Concerning to Figure 11, the first figure has an absolute immunity while the latter has half-immunity. At the point of E_{eq} of the first figure (active case), current immunities obtained by corrosion process(i_c) are formally the current immunity conditions(i_i), which means $i_c = i_i$. The reason why $i_c = i_i$ at this point is i_c is the sum of the corrosion rate (i_a) and i_i. As corrosion rate equals 0 at the equilibrium point, $i_c = i_i$. For the visual information, figure 12 is shown below.

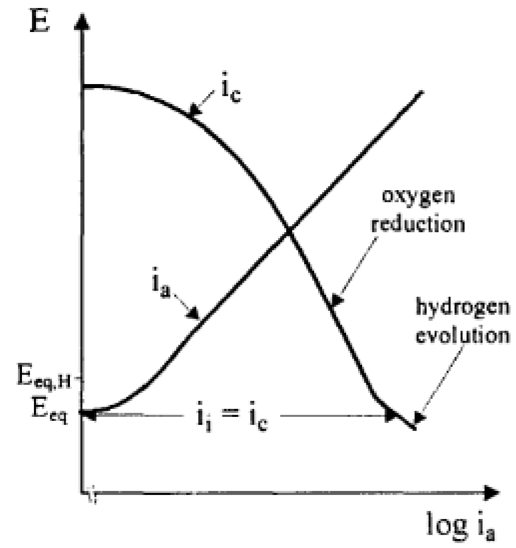


Figure 15. The schematic process of Cathodic Protection in active cases.[23]

The cathodic process does not directly affect the decrease of driving force. The interaction between cp and driving force occurs by the fact that decreasing of driving force regulates the corrosion passivity of the system or regulates a bigger environmental place. Fore more information, Figure 13 shown below illustrates the potential and its current which is required to achieve this potential. Also, it can be noted that how the decreasing of potential and the current required to achieve passivity ($E_{cor} - (E_p + i_i$)) are obviously smaller than the currents required to achieve immunity ($E_{cor} - (E_{eq} + i_i)$.

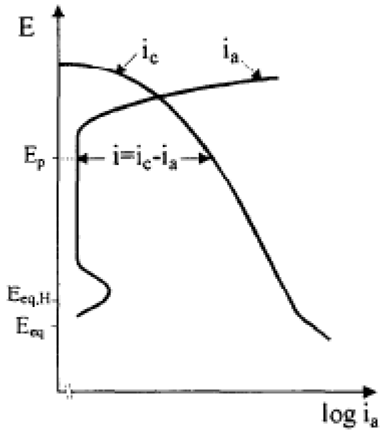


Figure 16. Active and Passive Behaviour of Cathodic Process [23]

The other benefit of the cathodic process is producing alkalinity on the surface and oxygen content reduction in which results in oxygen reduction and hydrogen evolution. These are the other effects that prevent corrosion because it leads to an extension of the passive area. If the surface remains not corroded it also leads to avoiding local acidification and pitting risk. (Figure 14)

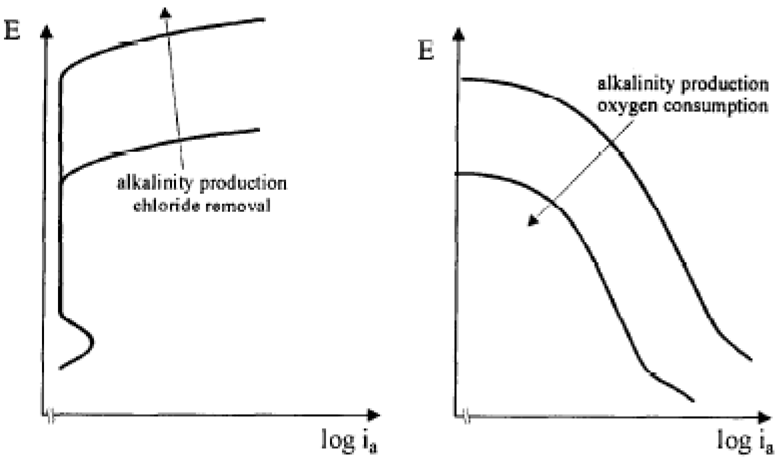


Figure 17. Schematic anodic(a) and cathodic(b) behavior of cathodic process in terms of alkalinity, oxygen consumption and chloride removal [23]

In addition, currents are transported by means of ion and in accordance with their charge. (positive currents moves together in the same direction and negatives move the opposite direction). Hence, in the concretes including chloride have a chloride flow starting from cathodic side to the anodic side. Although this current transportation can be minimized in normal situations, it may not be minimized for the concretes due to the amount of high current. In these circumstances, current circulation causes a drop in chloride component on the surface or a reduction in chloride penetration into concrete, establishing a kind of impermeable barrier that increases with the current.

The beneficial effect of decreasing potential can be noticed immediately as soon as the current is cut off. Whereas, although the changes caused by the cathodic process or the transportation of ions into the concrete maybe provide a beneficial result later than decreasing current, it may provide more long-term protection.

2.1.2. Significant Points to be Considered in Cathodic Protection

The beneficial effects of the cathodic process as mentioned above in terms of providing a long or short-term protection. Although the system is planned to be well-protected by cathodic protection, it may not be effective as expected. For example, one of the effective facts is decreasing the potential, however, if the potential is quite large compared to the cathodic process, it may not reach out the zero point or any point close to E_{eq} and increased hydrogen evolution takes place.

The cathodic process may also lead to a change in corrosive wear in terms of behavior and it causes hydrogen embrittlement problems. Furthermore, if the surface of the system is not well-protected by cathodic protection and mechanical wear attack occurs, hydrogen embrittlement increases [24]. It can be also noted that stress increases the dissolution of hydrogen. As a solution for this case, plastic deformation can take into account which leads to an increase of hydrogen diffusivity [25].

As a result, in a corrosive wear environment, a metallic material's resistance to surface failure could be controlled.

Other significant points to be considered are concrete degradation and adhesion loss. Concerning to concrete degradation, if the concrete contains an aggregate including a reactor against alkali, an increase in alkalinity surrounding the reinforcement might theoretically cause a failure. If the system contains aggregates that are alkali sensitive, the risk of alkali-silica reaction can be evaluated and minimized by lowering the current density.

Concerning to the last point, adhesion loss is also caused by the interaction between rebar and concrete. Possessing a high negative amount of potential may lead to an adhesion loss between concrete and rebar. According to research, -1.1 V can be the minimum limit of the potential in order to prevent adhesion loss. In addition, using a ribbed bar might be a solution for avoiding adhesion loss either [23].

2.1.2.1. Hydrogen Evolution of Cathodic Process

Hydrogen evolution of cathodic process occurs at the time when equilibrium potential of the hydrogen ($E_{eq,H}$) is greater than corrosion potential of metal (E_{corr}). The rate of $E_{eq,H}$ can be changed based on the pH value of steel but generally, it’s -950 mV.

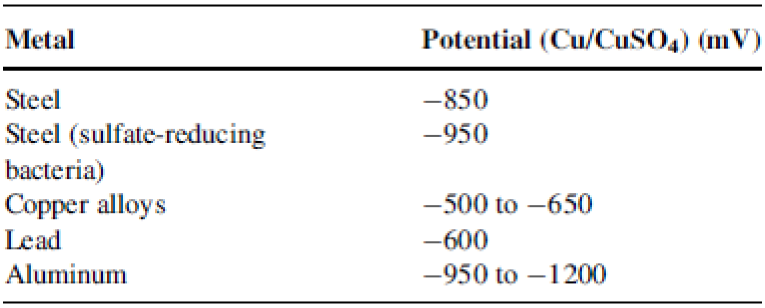
In contrast, metals located in more destructive areas have a higher corrosion potential than $E_{eq,H}$, which means $E_{corr} > E_{eq,H}$. In this situation, the corrosion rate can be calculated by $i_a = \frac{L}{R}$; where L is the driving force and R is anodic resistance, as mentioned in the Corrosion Rates part.

Hence, $E_{eq,H}$ should be considered as the minimum potential of cathodic process and more negative amounts cause a breakdown in mechanic performance of component due to increase of brittle fracture in which is also known as hydrogen embrittlement [32].

2.1.2.2. Potential of Components

In general, the potential of structure can be measured by means of reference electrode and values are referred to as copper/copper sulfate, pure zinc, or silver/silver chloride. To be able to measure efficiently, the reference electrode should be placed close to the surface to be measured. A frequently accepted protective potential for steel in an aerobic electrolyte with a standard pH is 850 mV, whereas, if its exposed to sulfate-reducing, a potential of 950 mV is necessary.

Some frequently used components potentials are illustrated in Table 7. As mentioned in the Hydrogen Evolution of Cathodic Process section, more negative values cause hydrogen embrtittlement. Furthermore, these components must be more under the control due to the risk of alkali accumulated on the surface of the component (i.e; Aluminum).



Metal	Potential ($Cu/CuSO_4$) (mV)
Steel	−850
Steel (sulfate-reducing bacteria)	−950
Copper alloys	−500 to −650
Lead	−600
Aluminum	−950 to −1200

Table 8. Protection Potential of Components

2.2. Types of Cathodic Protection

Cathodic protection systems are classified as either sacrificial anode or impressed current systems, depending on the type of polarization utilized to safeguard the structure.

2.2.1. Sacrificial Anode Cathodic Protection

A sacrificial anode (also known as a galvanic anode) is a metal with a lower potential than the structure metal to be protected. Galvanic anodes results quicker corrosion on sacrificial metal than structure metal has. Thus, the structure gets protected by corrosion.

Zinc and magnesium included alloys are commonly used as sacrificial anodes in the offshore environment, rather than using bronze propellers or other immersed approaches. On the other hand, aluminum and its alloys become more popular due to economic considerations but it becomes passive faster than zinc and magnesium, hence lowering the current output. Mercury, gallium, or indium can be used as an alloy for aluminum in order to prevent passivation [29].

The intention of a galvanic anode system is to send enough current through safeguarding a portion of the structure for the duration of the system's design life. This system of CP has been in use for many years, with zinc plates being used in place of bronze propellers and other immersed parts. At first, as the use of improper zinc alloys, the achievement of zinc anodes was not always good. By using modern anodes including zinc or aluminum alloys that have been subjected to extensive testing to ensure their appropriateness; high-purity zinc anodes are also utilized. The cost, along with a variety of other practical concerns, may affect which type is installed.

Sacrificial anodes generate their own power instead of using a source coming from outside, as well as it doesn’t require high maintenance. Concerning to maintenance, the design of the structure also affects the sacrificial system lifespan. It can be more suitable with structures that is well-coated against external damages. However, if aluminum-based material is used as a sacrificial anode, the surface of the system must leave without zinc coating after cleaning [30]. The other thing in order to design a more suitable system can be listed as;

1) The potential difference between sacrificial anode and corroded structure must be high in order to obtain a development anode and cathode cells in corroded structure.
2) Sacrificial anodes should not heavily polarized when current flows.
3) Anodes produced by metallic dissolution must be efficient for cathodic protection and freely be available for chemical reactions.

Sacrificial anodes are commonly designed as slender, flat-plate, long, flush- mounted type, standoff type and bracelet type. The most common shape is the long and slender type with trapezoidal. The intention of anode geometry is to obtain a high current output and effective current flow. For example, a slender type-shaped anode will have a greater anode current output than a flush-mounted one. Also, manufacturing and casting requirements are the other factors. Concerning manufacturing, flat-plates are the ideal choice for complex manufacturing where space constraints restrict the use of bigger stand-off anodes also where the cathode current densities are low such as heavily reinforced mud mats and flat or painted surfaces.

Stand off and flush mounted anode shapes can be classified based on their lenght-width ratio as it can be seen in Figure 15 and 15.1 and the selection of these shapes are related to anode resistance and utilization.

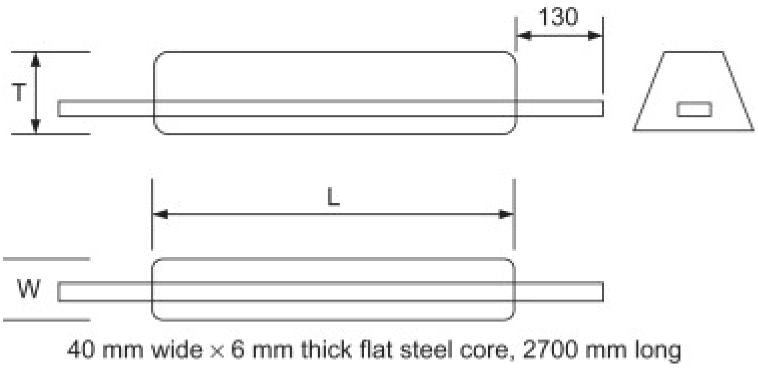


Figure 18.1. Flush mounted anode [30]

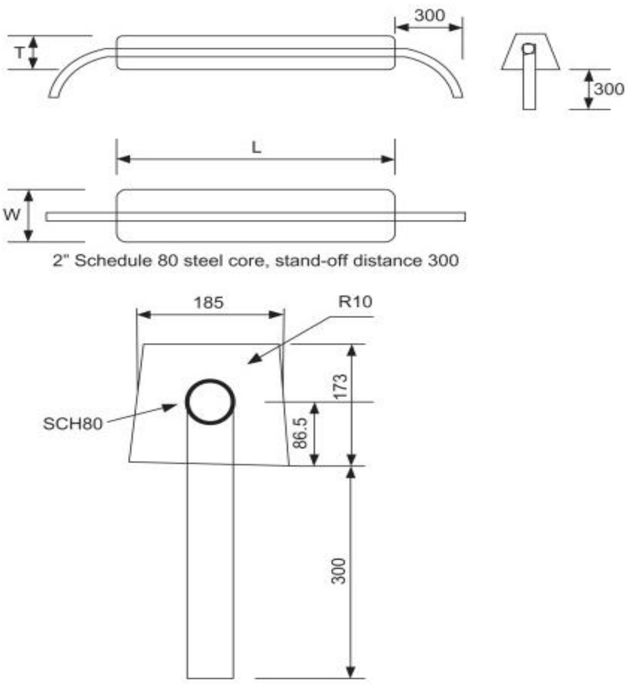


Figure 18.2. Stand off anode [30]

Stand off shaped anodes are commonly suitable for large anodes such as subsea templates. This type of anodes places the anode in a steel sled and secures it to the steel structure with a specific clamp. This method is simple to set up and less expensive to retrofit an existing structure.

Bracelet anodes were once largely utilized for pipelines, but they are now found on upper zone of platform legs, where they offer a high current-output-to-weight ratio while reducing drag.

Anode shape can be selected during the theoretical stage according to forces applied during the installation, during the pile installation, or wave effects. Stand off type anodes may be considered more carefully compared to other anode types, in order to get more efficiency.

Inside of anode design must be fit for anode weights and against the forces that may take place during the lifespan such as wave or storm damages, materials, or forces. Concerning to material selection, BS4360 grade 40A, 43A or 50C, or API 5L grades B, X42, or X52 can be utilized. As well as, NACE standarts must be followed and must meet the minimum limit S BS1706 [30].

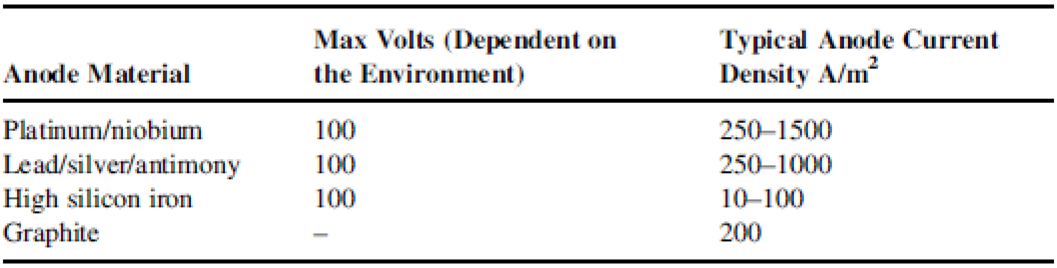
2.2.2. Impressed Current Cathodic Protection

Unlike sacrificial anode systems where current is driven by the total potential difference between anode material and structure, the impressed current system (ICCP) produces current by means of its own external source. During the lifespan of the CP, the electrical current output produced by the external source is adjusted in order to achieve and sustain an efficient potential level for protection over the structure to be applied. This system is commonly employed for the structures in which require high power demands, such as water storage tanks, or for the places are to be different current requirements. For this applications in which changeable conditions lead to a changing in current density, automatic potential control rectifiers is preferable in order to sustain adequate potential.

The requirements of ICCP can be listed as [31] ;

- DC Power Source
- External
- Circuit, connections, current cables
- System for monitoring
- Dielectric cover where is placed between cathode and anode in order to increase current distribution.
- Structure to be applied
- Reference electrodes

The most popular ICCP systems anodes are high silicon-cast iron, magnetite, graphite and platinized materials such as titanium or niobium. The current of ICCP system anodes can be up to 100 V and high current densities can be obtained. The benefit of this high current is protecting larger areas from a single anode compared to SACP and being able to control remotely due to an adequate amount of voltage. Table 8 shows the properties of impressed current anodes.

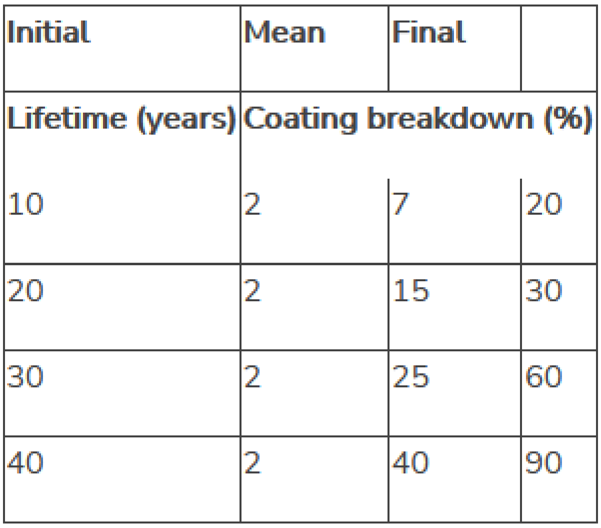


Anode Material	Max Volts (Dependent on the Environment)	Typical Anode Current Density A/m^2
Platinum/niobium	100	250–1500
Lead/silver/antimony	100	250–1000
High silicon iron	100	10–100
Graphite	–	200

Table 9. Properties of Impressed Current Anodes

2.3. Coatings

The intention of coating is to regulate an electrolytic pathway by putting a barrier between the applied metallic surface and the corrosive solution. If all the metallic surfaces can be well-coated with a substance that is completely waterproof and free of defects, all attacks from outside could be prevented. However, unfortunately, none of the coating and meticulous applications will guarantee an endlessly perfect coating. The error of coating starts with small flaws and increases by time. Table 10 shows the failure of coatings on offshore structures by the time.



Initial	Mean	Final	
Lifetime (years)	Coating breakdown (%)		
10	2	7	20
20	2	15	30
30	2	25	60
40	2	40	90

Table 10. Coating degradations of Offshore Structures. [33]

Concerning to coated and uncoated structure, it can be predicted that coated structure have fewer leaks over its lifespan but the first leak can be observed in coated structure due to the corrosion activation oriented from protected area through unprotected area. Furthermore, to be able to prevent this leak, a replacement will be required for this area. A new metal may have a tendency to become active metal (anodic) in terms of corrosive environment and coated structure may even have a worse situation by increasing of corrosion rate.

In order to avoid this case, if complete cathodic protection will not be employed with coating, at least, limited cathodic protection installations with sacrificial anodes, often known as "hot spot" protection, can be a cost-effective alternative in this case.

For the areas affected by stray current, it is crucial to apply an effective coating to the line in the part of the pickup current in order to boost resistance and decrease the total current that will lead to the structure's metal consumption when it discharges somewhere else. In this case, defining of current pickup is comparatively easy.

The effect of coating on cathodic protection can be easily observed in terms of the current required for protection. The decrease might be as high as 99.8% for a very good coating to as low as 50% for a severely bad, old, flawed coating [34]. To be able to obtain efficient protection, material selection is also important for decreasing.

2.3.1. Coating Types

Coatings generally contain three components; solvent, binder and pigment. But it can be changed in some examples. For instance, a coating that includes 100% solids does not have a solvent component. By using these materials, three types of coating can be obtained;

2.3.1.1. Inhibitor Coating

A protective barrier is placed to a metallic surface in the form of a solid, film, or fluid to eliminate corrosion. These barrier coatings have chemical or physical qualities that avoid external stimuli from causing corrosion reactivity and/or material breakdown.

2.3.1.2. Barrier Coating

A barrier coating creates an insulating and physical barrier, preventing corrosive materials, such as the electrolyte, from coming into contact with the substrate.

2.3.1.3. Sacrificial Coating

As applied in Sacrificial CP, sacrificial coatings are a type of selfless coating made of a metal, typically zinc, that corrodes more quickly than steel. In essence, this approach hijacks the corrosion process and directs it in a non-harmful direction for the asset the coating is supposed to preserve.

It should be noted that some types of materials used in coating applications are no longer available due to some significant reasons. For instance, chromate-based and coal tar anamel are no longer useable due to environmental risk and health-based problems. These materials are also more effective than other materials, hence, the current coating is not able to provide a better lifespan as it used to be. Therefore, cathodic protection takes place a significant role while applying with coatings. In addition, cathodic protection is not relatively useable for the structure regions where a high flow rate occurs. Therefore, the need for cathodic protection should be evaluated based on its location.

2.3.2. Coating Selection

Coating applications can be selected in terms of exposure status or environmental risks. On the other hand, having a variety of coating products to supply by manufacturers results in an accessible market. For the narrow or limited regions, brushable or rollable products are preferable over traditional spray or airless spray solutions. The use of coating on pipeline or flat structure surfaces can be applied faster but some additional materials are required. General considerations while selecting coating are;

In case of atmospheric exposure;

Alkyd-based materials or waterborne acrylics can be selected for good condition. For the best protection, zinc-based primer, polyurethane topcoat or galvanizing can be selected.

In case of submerged regions;

Epoxy, urethanes, polysiloxane or vinyl ester (restricted by Environmental Protection Agency's (EPA)) can be employed for efficient protection.

In case of buried exposure

AWWA C222 Polyurethane would be the best solution. Also, fusion bonded epoxy can be applied.

For a general coating selection, surface tolerant epoxy or moisture-cured urethane can be applied. This selection would provide efficient protection by sticking the edge of the flaw region.

2.3.3. Difficult regions to be coated

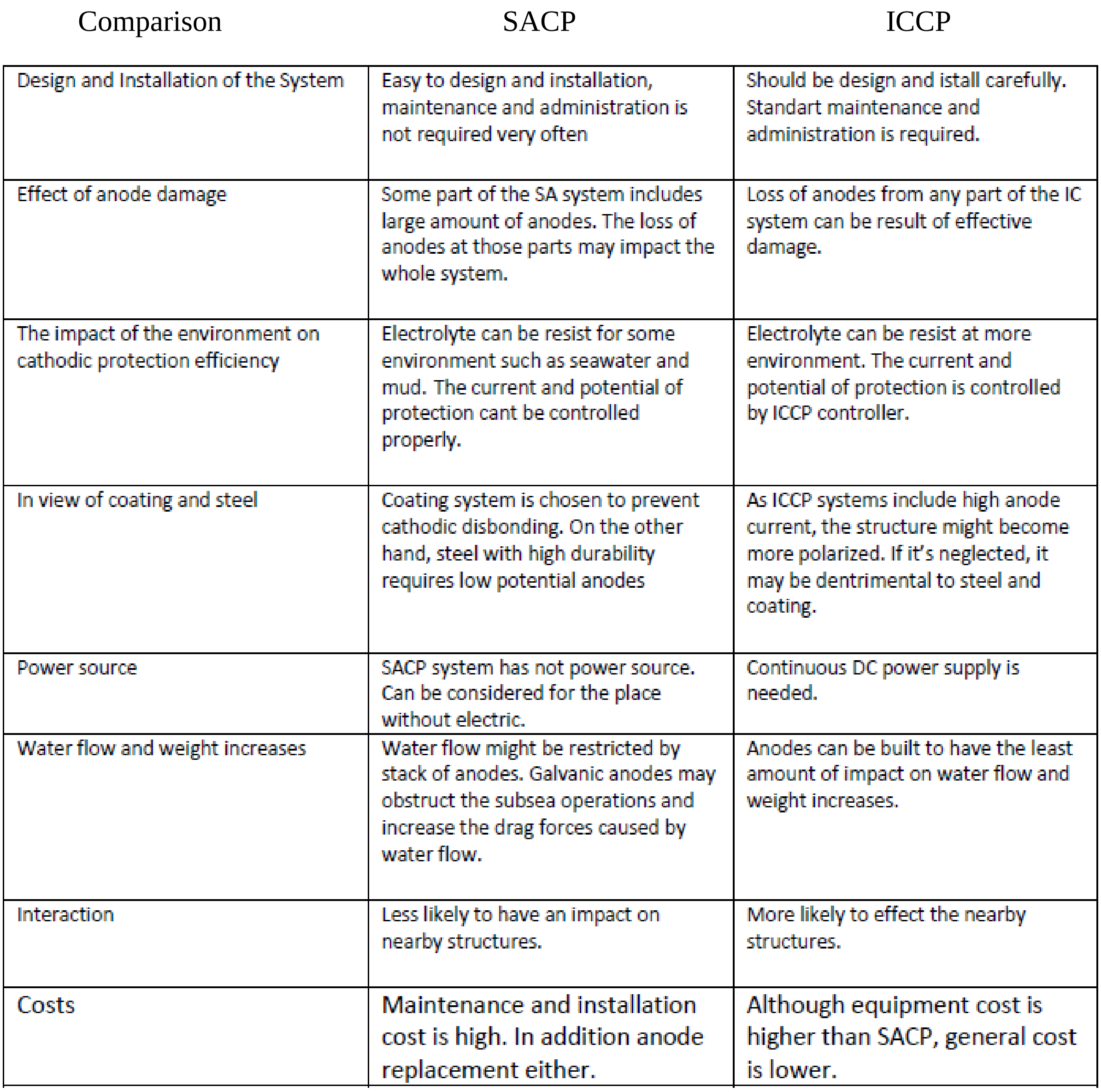
Unmaintained regions such as nailed connections, crevices, clinged structures or back-to-back plates might be faced with coating breakdown sooner. Although variety of coating types exist, most of them can be cracked easily as being crosslinked. Flexible caulking can be utilized to assist coating material but frequent maintenance might be required [35].

2.4. Combination of Coating and Cathodic Protection

- As mentioned previously, coating highly decreases the current demand for cathodic protection, hence also decreases the needed anode weight. Structures with weight-sensitive and long lifespans may lead to high costs during the corrosion process. In order to absorb a high amount of current demand and also stray current CP should be combined with coatings.
- Coating is also should be applied for the bare metal regions of the structures in which is expected to be high current. This is more relatively for deep-water applications where calcareous deposits may take a long time to build.
- For complicated and large systems such as multi-well oil&gas production systems, the coating should be applied extensively in order to control long-term current demand and provide an efficient current distribution.
- Coating may not be compitable for the immersed structure regions due to need of highly review for the fatigue cracks such as critical welded points of an immersed structure.
- Although metalic coating is suitable for the aluminum or zinc-based materials by applying for sacrificial cathodic protection, it’s not as suitable as organic coatings in terms of controlling the current demand of CP. Hence, zinc-rich materials are considered compitable for the combination of coating and CP due to either the way of its cathodic disownment or insufficient electrical resistivity, which results in high cathodic protection current demand.

2.5. COMPARISON OF ICCP SYSTEMS AND SACRIFICIAL ANODE SYSTEM

Use of Sacrificial Anodes Method or Impressed Current Method can be classified as it seem detaily in Table 11.



Comparison	SACP	ICCP
Design and Installation of the System	Easy to design and installation, maintenance and administration is not required very often	Should be design and istall carefully. Standart maintenance and administration is required.
Effect of anode damage	Some part of the SA system includes large amount of anodes. The loss of anodes at those parts may impact the whole system.	Loss of anodes from any part of the IC system can be result of effective damage.
The impact of the environment on cathodic protection efficiency	Electrolyte can be resist for some environment such as seawater and mud. The current and potential of protection cant be controlled properly.	Electrolyte can be resist at more environment. The current and potential of protection is controlled by ICCP controller.
In view of coating and steel	Coating system is chosen to prevent cathodic disbonding. On the other hand, steel with high durability requires low potential anodes	As ICCP systems include high anode current, the structure might become more polarized. If it's neglected, it may be dentrimental to steel and coating.
Power source	SACP system has not power source. Can be considered for the place without electric.	Continuous DC power supply is needed.
Water flow and weight increases	Water flow might be restricted by stack of anodes. Galvanic anodes may obstruct the subsea operations and increase the drag forces caused by water flow.	Anodes can be built to have the least amount of impact on water flow and weight increases.
Interaction	Less likely to have an impact on nearby structures.	More likely to effect the nearby structures.
Costs	Maintenance and installation cost is high. In addition anode replacement either.	Although equipment cost is higher than SACP, general cost is lower.

Table 11. Comparison between SACP and ICCP

CHAPTER 3

3. DESIGN CALCULATIONS AND PROCEDURES OF CATHODIC PROTECTION

3.1. General

If the area to be protected is large complex to calculate, the system can be subdivided based on zones or such as buried and submerged zones and detailed design should be maintained for each zone. After dividing each zones, anode types and relevant devices should be planned in accordance with forces applied on installed anodes during the operation. Furthermore, the coating to be selected should also be planned by following the coating categories, allowing for prior calculation of current demand by using the current densities and related total anode net mass needed for CP.

3.2. Design Calculations

3.2.1. Surface Area Calculation

Each zone should be measured separately without coating systems and also if any part of the system was affected by any condition (e.g. temperature), this part should also be measured separately, otherwise current demand will be a false result.

3.2.2. Current Demand

In order to obtain efficient polarizing capacity for the system and also provide adequate cathodic protection throughout its lifespan, current demand should be calculated for each zone's surface area by using the current densities (initial, mean and final) and coating breakdown factor.

Current demand can be calculated by using the formula shown below;

$$I_c = A_c * i_c * f_c$$

(10.3.1.)

Where;

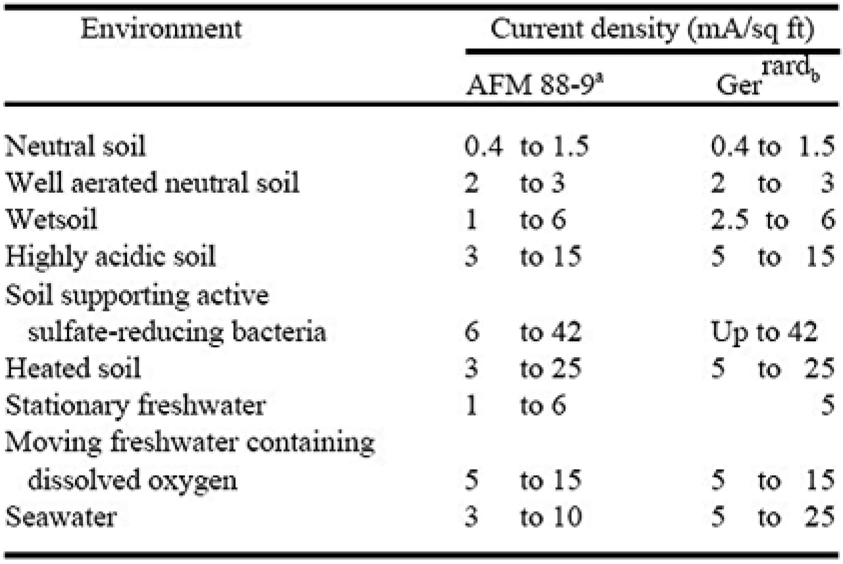
I_c : Current Demand (A)

A_c : Surface Area to be protected (A/m^2)

f_c : Coating breakdown factor

i_c : Current density

The coating breakdown factor for uncoated systems is assumed to be 1, which means there is no insulation by coating. This factor is explained detailly in the coating breakdown factor part. The other way of finding the total current requirement, also for uncoated systems, it can be estimated by using Table 12;



Environment	Current density (mA/sq ft)	
	AFM 88-9[a]	Gerrard[b]
Neutral soil	0.4 to 1.5	0.4 to 1.5
Well aerated neutral soil	2 to 3	2 to 3
Wetsoil	1 to 6	2.5 to 6
Highly acidic soil	3 to 15	5 to 15
Soil supporting active sulfate-reducing bacteria	6 to 42	Up to 42
Heated soil	3 to 25	5 to 25
Stationary freshwater	1 to 6	5
Moving freshwater containing dissolved oxygen	5 to 15	5 to 15
Seawater	3 to 10	5 to 25

Table 12. Current requirements for uncoated systems

3.2.3. ANODE MASS CALCULATION

After determining of current demand and anode selection, total anode mass calculation would be possible to obtain. In order to obtain total anode mass, (M_a), to be needed for lifespan, the formula is used as follows;

$$M_a = \frac{I_{cm} \cdot t_f \cdot 8760}{u \cdot \varepsilon}$$

Where;

I_{cm} : Current demand with mean current density

t_f: Design life

u: Anode utilization factor

ϵ : Electrochemical capacity of design

3.2.4. ANODE NUMBER CALCULATION

Based on the anode selection, total anode number (N), the mass of anode (M_a) and anode dimension should be obtained in order to meet the conditions for initial and final current (I_{ci} and I_{cf}) outputs and also anode current capacity (C_a).

Concerning to initial and final current outputs, individual current output (I_a) is measured by means of Ohm's Law.

$$I_c = N \cdot I_a = \frac{N(E_c{}^\circ - E_a{}^\circ)}{R_a} = \frac{N \cdot \Delta E^\circ}{R_a}$$

Where;

$\in_a$ °: Circuit design potential of anode selected (V)

R_a : Resistance of anode (Ohm)

I_a : Individual current output (are to be calculated for initial and final current separately)

$\in_c$ °: Potential of protective design

Concerning to anode current capacity, the formula is;

$$C_a = M_a * \varepsilon * u$$

Where;

M_a : Total anode mass

u: Anode utilization factor

ϵ : Electrochemical capacity of design

In order to make sure whether the calculation is correct or not, following formula can be used;

$$
\begin{aligned}
C_{a\,tot} &= N \cdot C_a \geq I_{cm} \cdot t_f \cdot 8760 \\
I_{a\,tot\,i} &= N \cdot I_{ai} \geq I_{ci} \\
I_{a\,tot\,f} &= N \cdot I_{af} \geq I_{cf}
\end{aligned}
$$

Where;

C_{atot} : Total amount of anode current capacity

I_{cf},I_{cm}, I_{ci} : Current demands based on each current densities

I_{ai} and I_{af} : Individual current outputs for initial and final current densities

3.2.5. CALCULATIONS OF ANODE RESISTANCE

Anode resistance, R_a (ohm), is calculated based on anode type as it can be seen in Table 13. While using these formulas, specific environmental parameters are required. (e.g. salinity,temperature,sediment factors etc.)

Anode Type	*Resistance Formula*
Long slender stand-off [1) 2)] $L \geq 4r$	$R_a = \frac{\rho}{2 \cdot \pi \cdot L}\left(\ln\frac{4 \cdot L}{r} - 1\right)$
Short slender stand-off [1) 2)] $L < 4r$	$R_a = \frac{\rho}{2 \cdot \pi \cdot L}\left[\ln\left\{\frac{2L}{r}\left(1+\sqrt{1+\left(\frac{r}{2L}\right)^2}\right)\right\} + \frac{r}{2L} - \sqrt{1+\left(\frac{r}{2L}\right)^2}\right]$
Long flush mounted [2)] $L \geq 4 \cdot$ width and $L \geq 4 \cdot$ thickness	$R_a = \frac{\rho}{2 \cdot S}$
Short flush-mounted, bracelet and other types	$R_a = \frac{0.315 \cdot \rho}{\sqrt{A}}$

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: $r = c/ 2\pi$ where c (m) is the anode cross sectional periphery

Table 13. Anode resistance formulas for each anode type [37].

The predicted dimensions when the anode has been employed to its utilization factor are used to compute the final anode resistance, R_{af} (ohm). At the end of the lifespan of the system, the remaining mass of anodes left from the use of utilization factor is obtained by the formula below;

$$m_{af} = m_{ai} \cdot (1 - u) \tag{10.1.}$$

Where;

m_{af} : final anode mass

m_{ai} : Inıtial anode mass

u : Utilisation factor

By using the final anode mass, final anode resistance can be found. When the volume of anode inserts is unknown, it should be ignored or given an approximate value to arrive at a suitable approximation.

3.2.6. ANODE CURRENT OUTPUT

The output of anode current can be found after anode resistance is obtained. It should be noted that this parameter must meet the current demand. The potential difference which is related to the performance of the metal is employed in anode current output formula as follows;

$$I_c = N \cdot I_a = \frac{N(E_c{}^{\circ} - E_a{}^{\circ})}{R_a} = \frac{N \cdot \Delta E^{\circ}}{R_a}$$

Where;

$\in_a{}^{\circ}$: Circuit design potential of anode selected (V)

R_a : Resistance of anode (Ohm)

I_a : Individual current output (are to be calculated for initial and final current separately)

$\in_c{}^{\circ}$: Potential of protective design

3.3. DESIGN PARAMETERS USED IN CALCULATIONS

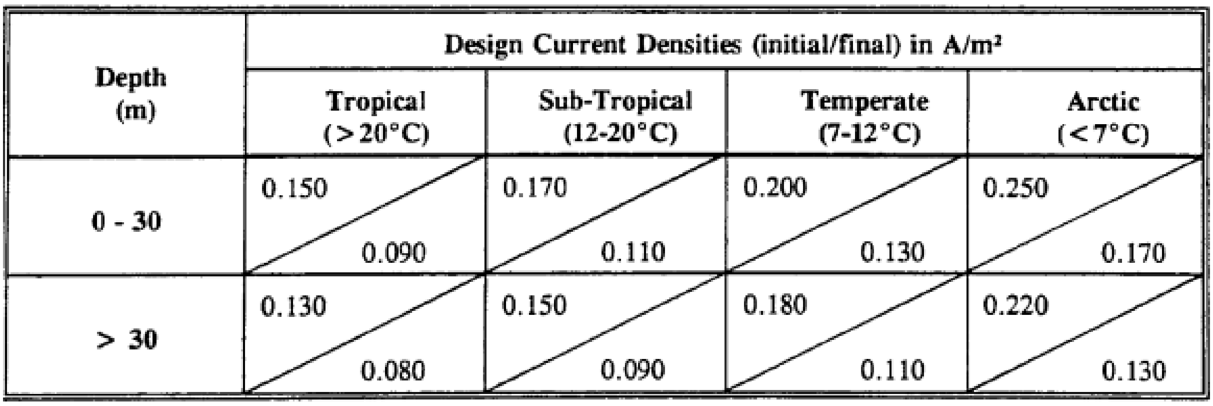
3.3.1. Design Life

Owners can typically specify the design life of a cathodic protection system in accordance with the probability of the protection object’s lifespan being extended. The lifespan must also account for any time when the cathodic protection system will be operational prior to the protection object's activity.

3.3.2. Design Current Density

Current density (I_c) can be explained as cathodic protection current per unit square meter. The initial, and final design current densities provide an estimate of the cathodic current density requirement needed to accomplish cathodic protection of a bare metal surface in a reasonable amount of time. As the cathodic protection system has reached its steady-state protection potential, the expected cathodic current density is measured by the mean design current density [36].

Current density is based on the local condition of the system. By increasing oxygen solutions on the system’s surface, current density also increases. Also pH, temperature and other environmental factors affect current density. Hence, current density should be selected based on weather condition which contains seawater and wave currents. Based on DNV-B401 recommendations, the current densities shown in Table 14 are utilized.



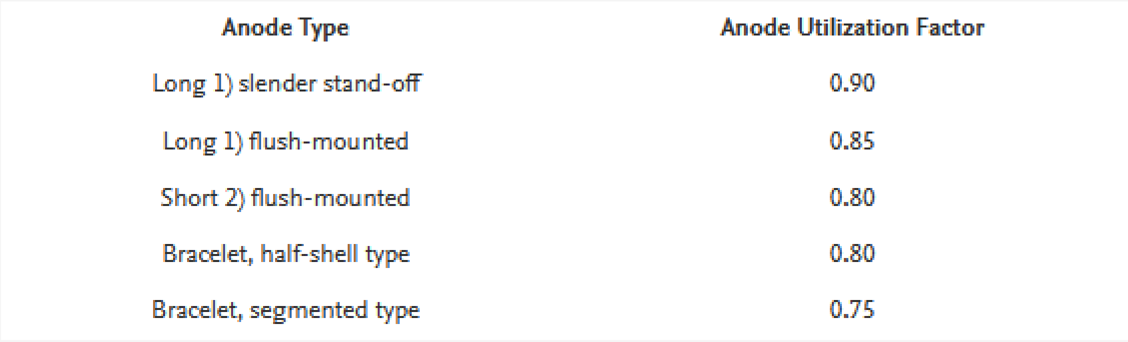
Depth (m)	Design Current Densities (initial/final) in A/m²			
	Tropical (>20°C)	Sub-Tropical (12-20°C)	Temperate (7-12°C)	Arctic (<7°C)
0 - 30	0.150 / 0.090	0.170 / 0.110	0.200 / 0.130	0.250 / 0.170
> 30	0.130 / 0.080	0.150 / 0.090	0.180 / 0.110	0.220 / 0.130

Table 14. Current Densities for Initial,mean and final parts in accordance with depth and local conditions based on DNV [37]

3.3.3. Anode Utilization Factor

This factor is the percentage of anode material that is thought to supply cathodic protection current depending on the anode design and location of anode sources. Once an anode is consumed its all utilization factor, due to the reason of anode loss or a sudden increase in anode resistance for some reasons, polarizing capacity, which is regulated by anode current output, cannot be measured.

Based on DNV RP B401 recommendations, utilization factors of anode designs shown in Table 15 are used in order to calculate the CP design [37].



Anode Type	Anode Utilization Factor
Long 1) slender stand-off	0.90
Long 1) flush-mounted	0.85
Short 2) flush-mounted	0.80
Bracelet, half-shell type	0.80
Bracelet, segmented type	0.75

Table 15. Anode utilizations of common anode designs based on DNV recommendations.

3.3.4 Coating Breakdown Factor (f_C):

The coating breakdown factor expresses the increase of the reduction in current density (I_c) due to coating. Coating qualities, operational conditions, and time all influence the coating breakdown factor. The value of the coating breakdown factor is measured between 0 to 1. The result of 0 means that the electrical insulation of coating is 100%, whilst, the result of 1 means that the coating is not able to provide any electrical insulation.

f_C, can be estimated as follows;

$f_C = k_1 + k_2 * t$

Where;

t : lifespan of coating

$k_1 + k_2$: constant values of coating properties

In soil, there are four paint coating categorized in terms of the influence of f_C on the coating system based on DNV B401 recommendation [37].

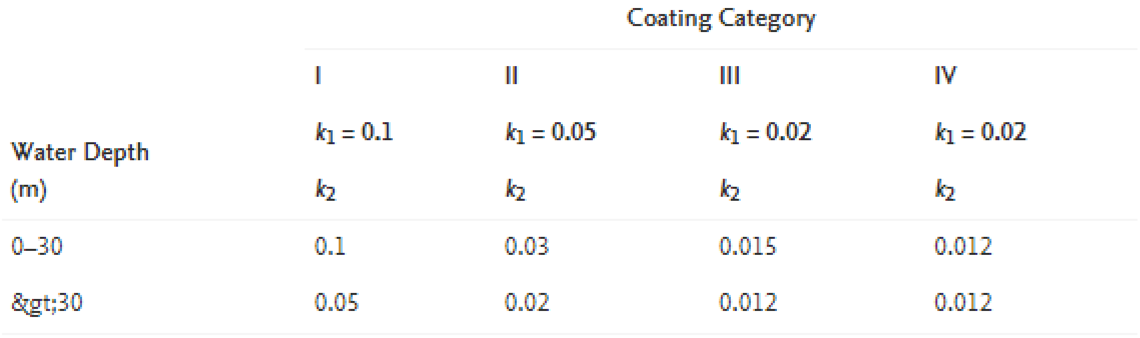
Category 1: Primer coat which is 50 µm nominal DFT (dry film thickness).

Category 2: Primer coat and one layer of coat for top, 150–250 µm nominal DFT.

Category 3: Primer coat and two layers of coat for top, 300 µm nominal DFT.

Category 4: Primer coat and three layers of coat for top, 450 µm nominal DFT.

Concerning to k_1 and k_2 constants, table 16 is used based on water depth.



	Coating Category			
	I	II	III	IV
Water Depth (m)	$k_1 = 0.1$ k_2	$k_1 = 0.05$ k_2	$k_1 = 0.02$ k_2	$k_1 = 0.02$ k_2
0–30	0.1	0.03	0.015	0.012
>30	0.05	0.02	0.012	0.012

Table 16.Calculations of constants of coating breakdown factor

Also, mean and final coating breakdown factors are significant for cathodic protection design. Equations of mean and final are given below;

$f_C(mean)$ = $k_1 + k_2 * t/2$

f_C (final) = $k_1 + k_2 * t$

3.3.5. Current Drain Design Parameters

All components in which are electrically connected in the CP system should be taken into account in the current drain calculation. In order to calculate the current drain for the structures that CP is not required, current density and coating breakdown factor should also be used while current drain calculation.

For the part of complex offshore structures in which CP is not required for the system but these parts can easily tolerate coatings such as skirts and piles, the current drain can be considered as 0.020 A/m^2 or 0.025 A/m^2. It depends on the external area of the system to be buried in sediments. For the good coating, the current drain is considered to be 5 Amps per well in the current drain calculation. Compared to platform wells, subsea wells are more current drains due to the use of cement. However, subsea wells might be faced with a crucial current drain while installing, hence, 8 Amps per well should be considered.

For the current drain of anchor chains including mooring at the top side only, 30 meters of each chain should be taken into account in CP design. If the mooring system locates at sea level of the system, CP design should be considered between the chain part exposed to seawater and mooring point as well as 30 meters from the mooring point for each chain.

CHAPTER 4

4.1. ANODE MANUFACTURING

4.1.1. Requirements

The before and after the casting process of sacrificial anodes is defined in this part. The requirements for this part are similar to NACE RP0387 requirements, with a few exceptions, the most important of which are linked to quality control. Requirements can be classified partly for manufacturing procedure, coating, testing, inspection and quality control of anode.

4.1.2. Manufacturing procedure

A preproduction test must be performed before the job is getting started to ensure that all molds, inserts, casting materials, and other components are in compliance with suitable codes of practice, ruling drawings, and datasheets. A casting test is required to show that all of the stipulated requirements can be reached. For the orders above 15-ton net, “manufacturing procedure specification (MPS)” should be arranged. In case of below than 15-ton net orders, a special agreement for testing should be arranged with the purchaser.

4.1.3. Coating

The coating should not be designed for the external part of the anode. Concerning to anode shapes, flush mounted and bracelet can be coated from the side used cement or lining. The minimum amount of coating for these shapes is 100 microns epoxy mastic.

4.1.4. Pre-production quality test (PQT)

The main intention of the PQT is to make sure that MPS is whether efficient to supply the selected anode properties or not. As PQT is combined with MPS, 15 tons net and more amounts are tested in general but a lower amount can also be tested by the purchaser's request. After getting the results from PQT (by means of MPS and inspections), a detailed schedule is shared with the purchaser before the job is getting started.

4.1.5 Quality Control of Anode

The main intention of quality control is to identify improperly produced components that are not realized while manufacturing specifications, potentially resulting in arguable performance. Chemical test of the anode alloy is commonly performed using spark emission spectroscopy, which is also known as primary quality control check. For the surface preparation of this testing, especially for the small amount of anodes must be confirmed to provide that analysis is not tainted by the surface preparation. This risk can be reduced when the analytical approach employs the dissolving of the sample instead of surface preparation.

4.1.6. Inspection and Testing of Anode

Anode inspection should be handled by a corrosion specialist to ensure that anodes are not taken any damage while inspection. Based on DNV recommendation, chemical analysis (i.e. anode heat test) of anodes should be carried out by means of NACE RP0387.

The owner has the option of requiring anode sample material for verification testing from the laboratory or presenting samples for the Owner's testing. The owner can further require that the Contractor keep the sample material for any relevant chemical and/or electrochemical testing. All anodes in which don’t meet the requirements in testing should be rejected.

NACE RP0387 may also be applied for anode weight and distance while inspection. The positions of protruding errors must conform to the manufacturer's specifications and be tested for a minimum of 10 percent of the anodes in a specific design. The owner can require an additional inspection for anode dimensional tolerances.

Concerning to crevice regions of the system, inspection varies depending on the type of anodes that is used.

- For zinc included anodes, crevices should not be seen by naked eyes.
- Anode inserts are not allowed if cracks may be seen penetrating them.
- Crevices wider than 2 millimeters are only tolerated within the section entirely supported by anode inserts if the length is less than 100 millimeters.

On all anodes, any coating to be designed must be visually inspected. Coating spills on surfaces not meant for coating must be cleaned up.

The lowest amount of two anodes for each size should be selected for destructive testing in order to ensure avoid internal faults and proper placement for anode inserts. NACE RP0387 or cutting procedure is preferable for this testing. If it’s possible, this type of testing can be applied in PQT process. If PQT is not being planned, destructive testing must be done on the first day. The owner has the option of selecting anodes to be used in testing.

Electrochemical testing should be done in PQT process or for anode orders of more than 15000 net kg. The owner may also require additional tests. For the application of electrochemical testing, requirements for testing must be obtained for each heat supplied.

Failures during testing that are clearly related to faulty samples or testing material operating problems can be ignored, and testing on the same anode resumed. If a failure occurs in fractional testing for an anode, prior and the next 3 anodes (minimum) must be tested individually to ensure that testing for the following anodes is suitable [37].

4.2. MAINTENANCE and OPERATIONS

After the installation of CP system, some certain operations are followed in order to prevent current or next failure. The failure that occurred in the CP system is not always visible or solvable remotely. For instance, if there is a potential fall on the pipeline system through the soil, corrosion damages the pipeline slowly and out of sight (except special equipment to provide visibility). Furthermore, no one can notice this failure until a leak takes place and when it’s realized it may be too late for the system concerned in terms of lifespan.

As in the example of pipeline potential fall to the soil, there are other failure signals based on offshore structures concerned. These failures may pay more attention to the maintenance workers during the operation applying regularly and workers come up with a solution for the system before it’s too late. This maintenance should be guided by operators or manufacturers. Some common failures for SACP and ICCP systems are mentioned below.

4.2.1. Rectifier Ground-Bed Transformer Failure in ICCP

It should be noted that this failure can be seen in any part of the system although that area is being protected. In ICCP applications, the following components of the system should be taken into account in order to prevent failures [38].

- The power supply
- Cable connections in the whole system; to prevent low connection and provide more protection.
- Complete rectifier components such as circuit breaker, transformer, or stacks.
- The ground bed of the system; anodes may have a problem for any reason which leads to an increase of total resistance. Thus a change may occur in soil content.
- Coating; breakdown may occur in the coating over time and results in an increase of system demand.

4.2.2. Sacrificial Anode System Failures

As sacrificial anode systems include various drainage points, there may be some failures in small regions of the system. Hence, it should be noted that even small regions must be controlled by operators to ensure that the whole network is running properly. In SACP applications, the following topics should be taken into account in order to prevent failures.

- Mechanical damage control to the connections.
- Dry soil may affect the current output negatively, thus a failure may occur in the structure or anodes.
- As in ICCP failure, coating breakdown may also result in an increase in system demand for the SACP system.

This failure mostly will be revealed by the failure of current output as in ICCP systems. Although this failure is not always visible, it can be under control if it is measured by means of a shunt or an ammeter can be installed [38].

Chapter 5

Experimental work and analyses

The main intention of this thesis is to explain the design of cathodic protection for the offshore structures and make design calculations for each coated and uncoated cathodic protection thus, providing a discussion in accordance with its anode size. Designing sacrificial for the external surface of a hypothetical construction to be placed in 30 meters of water off the coast of the Canary Islands is a recommended practice. The reason for selecting the Canary Islands is the Spanish Wind Energy Association, Asociación Empresarial Eólica (AEE), which aims at least 3 GW of offshore wind turbines that can be built in Spain by 2030 and the most considered place is the Canary Islands. These calculations will be measured based on DNV RP B401 recommendations as applied in the previous sections. The flow of the design calculations is as follows in Figure 16.

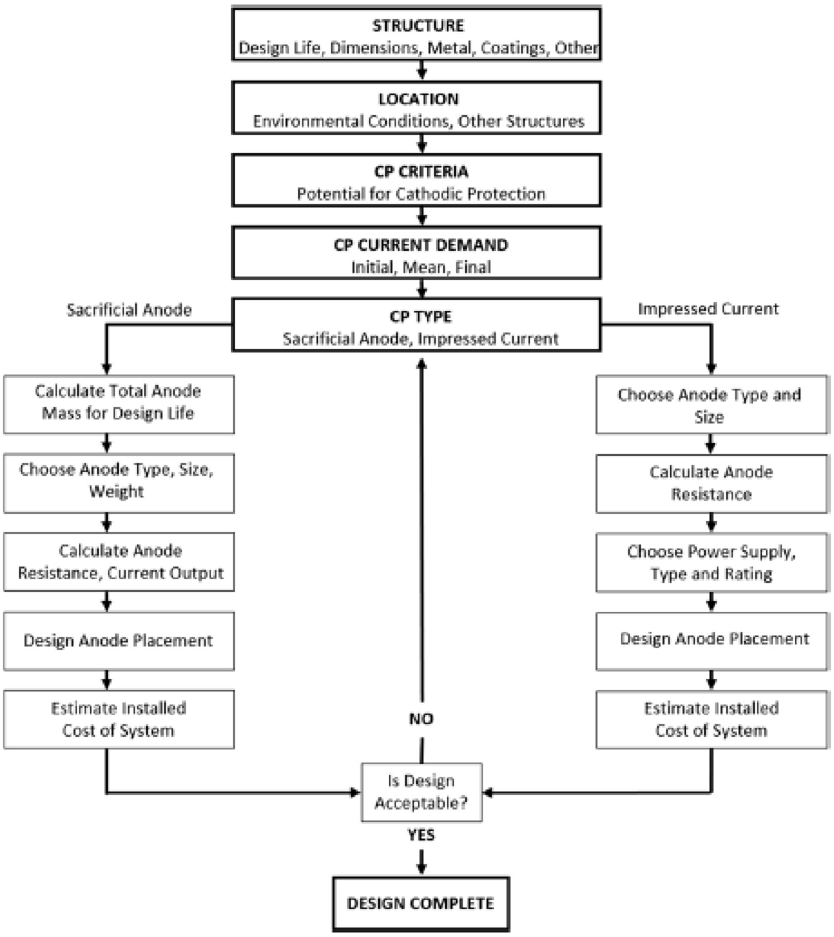


Figure 19. The flow of design calculation [45]

Monopile foundations are the most often utilized wind turbine foundation due to their ease of construction compared to other foundation types. Although most of the offshore wind turbines are anchored to the seafloor up to 50-meter depth (except floating wind turbines which is connected to the sea bed with mooring lines), 40-meter and lower depths are the most convenient levels in terms of technical advantages and monopile foundation provides a better condition at this level. Hence, monopile foundation is decided for wind farm foundation concerned.

Both internal and external sections of the monopile structures can be affected by corrosion. Concerning to external part, the coating should be applied for the splash and atmospheric zones whereas CP is applied for the submerged zone of the wind turbine as mentioned in previous sections. The internal part of the system also interacts with corrosion and corrosion control should also take into account. In order to prevent, if the internal part is confined from the air entrance corrosion control can be achieved however, prevention of entire amount of air is impossible for these systems, hence, CP or a coating system may provide a better manner for prevention. According to previous experiences, the use of SACP for internal protection increases the acid level of the water concerned [39]. Furthermore, when SACP is implemented for the internal part, an important change in hydrogen level is not observed except increasing of hydrogen sulfide level [40]. For maintenance, changing of 5% water from J-Tube parts is compulsory every day [41]. As internal cathodic protection would be costly and can’t be monitored well due to the restricted area of the internal surface, a coating may not be employed. For this experiment, internal parts have been left uncoated.

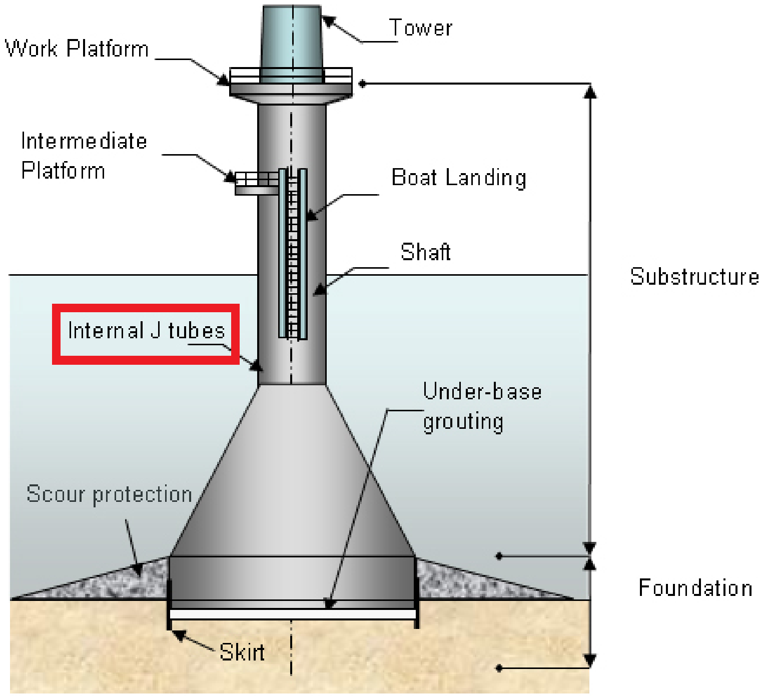


Figure 20. Internal J Tubes for daily seawater changing [45]

For the external part, it has been noted that a high amount of anode needed for protection interacts with each other which results in protection for the submerged part since anodes are being stacked. Hence instead of using a high amount of anode, coating is the alternative way to provide protection as the current demand is reduced. For anode type selection, stand – off anode can be employed. Based on coating quality which is categorized by DNV B401 recommendation, up to 80% insulation can be achieved by using Category 3 coating for stand – off anode aluminum anode mass [42]. Flash mounted anode will also be applied in order to classify the difference between stand-off anode and flash mounted. As common standards will be followed, both anode shapes will be considered to be 100 kg weight [30].

Calculation Procedure of DNV B401

In order to follow the flow of the Sacrificial Anode calculations surface area of the external part, environmental parameters, current demand, anode mass, steel type, total current output and anode resistance should be obtained (Figure 17).

Structural and Environmental Parameters

Related parameters for the monopiles are;

Outer diameter: 8 m

Wall thickness: 120 mm

Total length: 90.5 m (50 m buried zone, 40 m column of seawater, 0.5 m mean water line (MWL))

A transition piece (TP) connects the monopile part to the upper part. This piece starts from below sea level and stretches through the intertidal and splash zone as it can be seen in Figure 18. For design calculations, this part can be neglected.

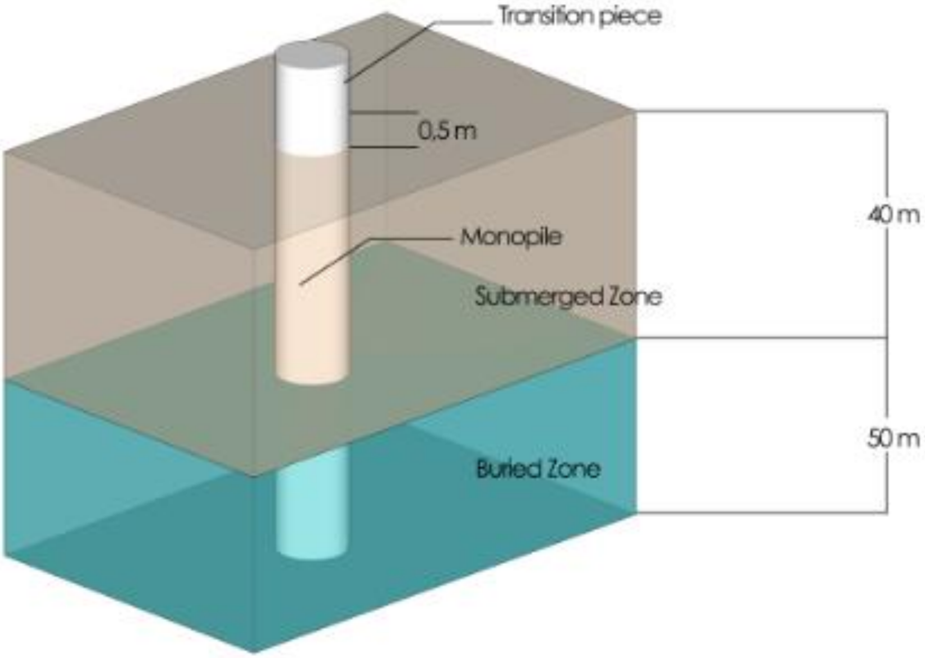


Figure 21. Zones of Monopile Foundation

The structure will be located 20 km away from the Southeast of the Gran Canaria Island's coast. According to Puertos del Estado, a Spanish government's port agency, water temperature for the bottom part ranges from 15 to 25 degrees [44]. The other seawater parameters are salinity and dissolved oxygen of approximately 34,32 and 5,63 mg/L [44]. The Sedimental current of the southeast part of Canary Island is 30-40 cm s^{-1} [43]. Finally, the average wave height is 1.25 to 2.7 meters [44].

In general, a modern wind turbine of acceptable quality will typically last 20 years, however, this can be extended to 25 years or beyond depending on environmental circumstances and proper maintenance practices. However, as the structure ages, the maintenance expenses will rise. In this lifespan, as tidal and splash zones are exposed to coverence of the transition piece, severe corrosion rates occur due to occasionally drying and wetting conditions and oxygen concentration. If cathodic protection is applied for this zone, it will be inefficient due to deficiency of submerged seawater, hence, the coating is utilized for this region. Barrier coating will be designed for this region and it also meets the design life of the structure by lasting about 20 years.

Calculations and Results

Calculations of Surface Area :

To begin with, the surface area of the external part which is consists of buried, submerged and splash zones was measured first. In order to obtain the CP current demand, the steel surface area to be protected was multiplied by the initial, mean and current densities needed to accomplish the polarization and keep the potential more negative value than -0.800 V based on silver/silver chloride electrode. As the coating breakdown factor takes into account the coated places, current demand is minimized. Concerning to anode mass needed for the whole design lifespan, mean current density is employed. On the other hand, the initial current density is employed to stimulate quick calcareous deposit formation which will get minimized the system current demand over its anticipated lifespan. And finally, the final current density is employed when the calcareous part and connected fouling are partially removed by means of waves or other conditions. To sum up, all densities are required in order to obtain CP's current demand [45]. As temperature varies between 15 to 25 degrees, subtropical conditions of current densities for seawater exposed bare metal surfaces are used (Table 16).

Sub-Tropical (12-20°C)			
Depth (m)	Initial	Mean	Final
0-30 m	0,170	0,080	0,110
30-100 m	0,140	0,070	0,090

Table 17. Current densities based on Canary Island conditions.

Zone	**Length (m)**	**Surface Area (m^2)**
Mean Water Line	0,5	113,098
Submerged	40	1105,84
Buried	50	1357,17

Table 18. Calculations of Surface Area to be protected

In order to obtain current demand, the formula is used as follows;

$$I_c = A_c * i_c * f_c$$

Surface areas (A_c) are found in table 18. Also, the suggested current densities for the subtropical environment are provided in table 17. As design current densities are dependent on regional depth and temperature, each region will be found separately. For the buried region, the current density is 0.020 A/m^2[37].

The use of coating decreases the current demand. This reduction depends on the category of coating and DNV – RP – 401 guidance will be followed in this calculation. According to DNV, the categories are;

Category 1: Primer coat which is 50 µm nominal DFT (dry film thickness).

Category 2: Primer coat and one layer of coating for top, 150–250 µm nominal DFT.

Category 3: Primer coat and two layers of coating for top, 300 µm nominal DFT.

Category 4: Primer coat and three layers of coating for top, 450 µm nominal DFT.

For the uncoated regions, the coating breakdown factor is assumed to be 1. For coated regions, k_1 and k_2 values stated in Table 16 are employed separately for each initial, mean and final part. And finally, values are calculated by the formulas below;

f_C (initial) = $k_1 + k_2 * t$

$f_C(mean)$ = $k_1 + k_2 * t/2$

f_C (final) = $k_1 + k_2 * t$

The results of each category for a 25-year design lifespan are shown in table 19. As the coating breakdown factor can't be greater than 1, the values greater than 1 were shown as 1. After obtaining each coating breakdown factor, current demand is obtained as it seen in Table 20 and the total current demand for CP can be found by summing up each zone's result (Table 21).

Depth (m)	**Coating Breakdowns**	**Uncoated**	**Category 1**	**Category 2**	**Category 3**
0 – 30 m	Initial	1	1	0,8	0,395
	Mean	1	1	0,425	0,2075
	Final	1	1	0,8	0,395
30+ m	Inıtial	1	1	0,55	0,32
	Mean	1	0,725	0,3	0,17
	Final	1	1	0,55	0,32

Table 19. Results of each Coating Breakdown Factor categorized

According to results in Table 19, Category I has the lowest reduction compared to Category II and Category III. It must be noted that Category II and III provide a better convenience in terms of current demand. Current demand results for each zones are provided in Table 20 by using the coating breakdown factor. As the inputs to be used for calculation will be different at 30 meters and more depths, calculations for the submerged zone is divided into 2 calculation.

Depth (m)	Zone		Uncoated	Cat I	Cat II	Cat III
0-0,5	MWL	Initial	19,22	19,22	15,38	7,59
		Mean	90,47	90,47	38,45	18,77
		Final	12,44	12,44	9,95	4,91
0,5-30	Submerged	Initial	145,27	145,27	116,21	57,38
		Mean	683,60	683,60	290,53	141,85
		Final	94,00	94,00	75,20	37,12
30-40,5	Submerged	Initial	49,14	49,14	27,09	15,76
		Mean	24,62	18,85	7,38	4,18
		Final	31,66	31,66	17,41	10,13
40,5-90,5	Buried	Initial	190,00	190,00	104,50	60,80
		Mean	95,00	68,87	28,50	16,15
		Final	122,14	122,14	67,18	39,08

Table 20. Current Demand results for each zone

Totals	Uncoated	Cat I	Cat II	Cat III
Initial	403,63	403,63	263,18	141,53
Mean	893,69	861,79	364,86	180,95
Final	260,24	260,24	169,74	91,24

Table 21. Total Current Demands

Mass of Anode Calculation

As it stated before, anode mass is calculated by the formula below;

$$M_a = \frac{I_{cm} \cdot t_f \cdot 8760}{u \cdot \varepsilon}$$

Where;

I_{cm} : Current demand with mean current density

t_f: Design life

u: Anode utilization factor

ϵ: Electrochemical capacity of design

Current demand with mean current demand and design lifespan parameters are already known. 8760 is the total hours of an entire year. The reason why mean current demand is employed in anode mass formula is final and initial current demands do not stand in a constant value. Concerning to anode type, aluminum was selected due to its economic aspect and electrochemical efficiency of having less weight requirement compared to zinc or magnesium. However, these factors shouldn't be the only reasons for anode selection. For instance, stand off aluminum anode may provide a suitable condition in terms of weight or electrochemical efficiency but these conditions may also affect the wave loading of the structure in a negative manner throughout its design lifespan. The utilization factor of stand off and flush mounted anodes are 0.90 and 0.85 as it can be seen in Table 15 with the DNV recommendations. According to DNV recommendation in Annex A, the electrochemical capacity of design, ϵ, recommended value is dependent on zone to be calculated and these values are preferable up to 30° average yearly degrees. Based on this recommendation, the Aluminum based electrochemical capacity for seawater is 2000 Ah/kg and for the sediment zone is 1500 Ah/kg [37].

The result of anode mass calculations are provided in Table 22 below;

	Uncoated	Cat I	Cat II	Cat III
Stand-off	108732,2	104851,1	44391,3	22015,5
Flush mounted	115128,3	111018,8	47002,5	23310,6

Table 22. Anode mass calculations

Number of Anode Calculations:

Anode number must be suitable for the requirements below;

$$
\begin{aligned}
C_{a\,tot} &= N \cdot C_a \geq I_{cm} \cdot t_f \cdot 8760 \\
I_{a\,tot\,i} &= N \cdot I_{ai} \geq I_{ci} \\
I_{a\,tot\,f} &= N \cdot I_{af} \geq I_{cf}
\end{aligned}
$$

Where;

I_{cm}: Current needed for a design life

$I_{a\,tot\,i}$: Total initial current demand

$I_{a\,tot\,f}$: Total final current demand

C_a: Current capacity for each zone

$C_{a\,tot}$: Total current capacity

I_{ai}, I_{af}: Individually initial and final current outputs

Hence, current capacity should be known first in order to calculate the anode number. In order to obtain current capacity for both coated and uncoated design, the value of anode mass along with electrochemical capacity and utilization factor are used in the formula as follows;

$$C_a = m * \epsilon * u$$

Where ;

m = anode mass (kg)

ϵ = Electrochemical capacity (Ah/kg)

u = Utilization factor (Ohm)

The anode dimensions must be planned in such a way that the anode numbers are needed to provide current demand during the design lifespan and also meet current output requirements for both initial and final polarization.

Anode Current Output:

The output of anode current must meet the initial and final current demands. As it stated before, Ohm's Law formula is applied for obtaining current output.

$$I_c = N \cdot I_a = \frac{N(E_c{}^\circ - E_a{}^\circ)}{R_a} = \frac{N \cdot \Delta E^\circ}{R_a}$$

Where;

$\in_a$ °: Circuit design potential of anode selected (V)

R_a : Resistance of anode (Ohm)

I_a: Individual current output (are to be calculated for initial and final current separately)

$\in_c$ °: Potential of protective design

Individual results can also be found by removing N in the formula. $\Delta E°$ is the difference of steel potential and anode closed-circuit potential; hence, -1.05 V – 0.8V in silver/silver chloride reference. Moreover, anode resistance, R_a, should also be obtained individually for Stand-off and Flush mounted anode geometries with the equations below. In determining of final anode resistance for both anode geometry, the final length can take into consideration as 10% shorter than the initial length.

For stand-off:

$$R_a = \frac{\rho}{2 \cdot \pi \cdot L}\left(\ln\frac{4 \cdot L}{r} - 1\right)$$

For flush mounted:

$$R_a = \frac{\rho}{2 \cdot S}$$

Concerning to geometric shape of stand-off, their geometry usually adopts the dimensions which are more trapezoidal due to being placed into the molds. In order to obtain the radius of stand-off, the square root of the cross-sectional area should be divided by pi. This radius value, along with anode length and seawater resistance, is used to create a formula for calculating anode resistance.

Concerning to geometric shape of flush mounted, seawater resistance and the arithmetic average of anode width and length should be employed. Seawater resistance is provided as follows, by using the salinity and temperature parameters. The minimum temperature and salinity of the selected location are 15 and 34,32 mg/L. Hence, seawater resistance is 0.26 Ω·m.

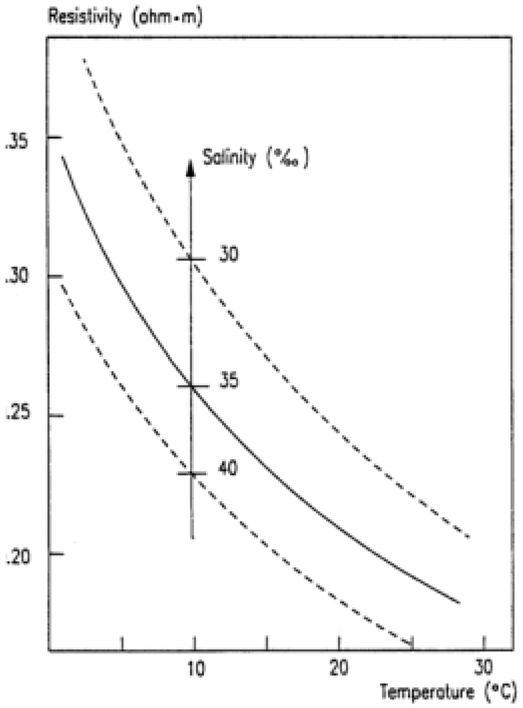


Figure 22. Seawater resistivity by using temperature and salinity [37].

After obtaining anode resistance for both initial and final, the remaining mass of anodes left from the use of utilization factor was found by the formula below;

$$m_{af} = m_{ai} \cdot (1 - u)$$

Where;

m_{af}: final anode mass

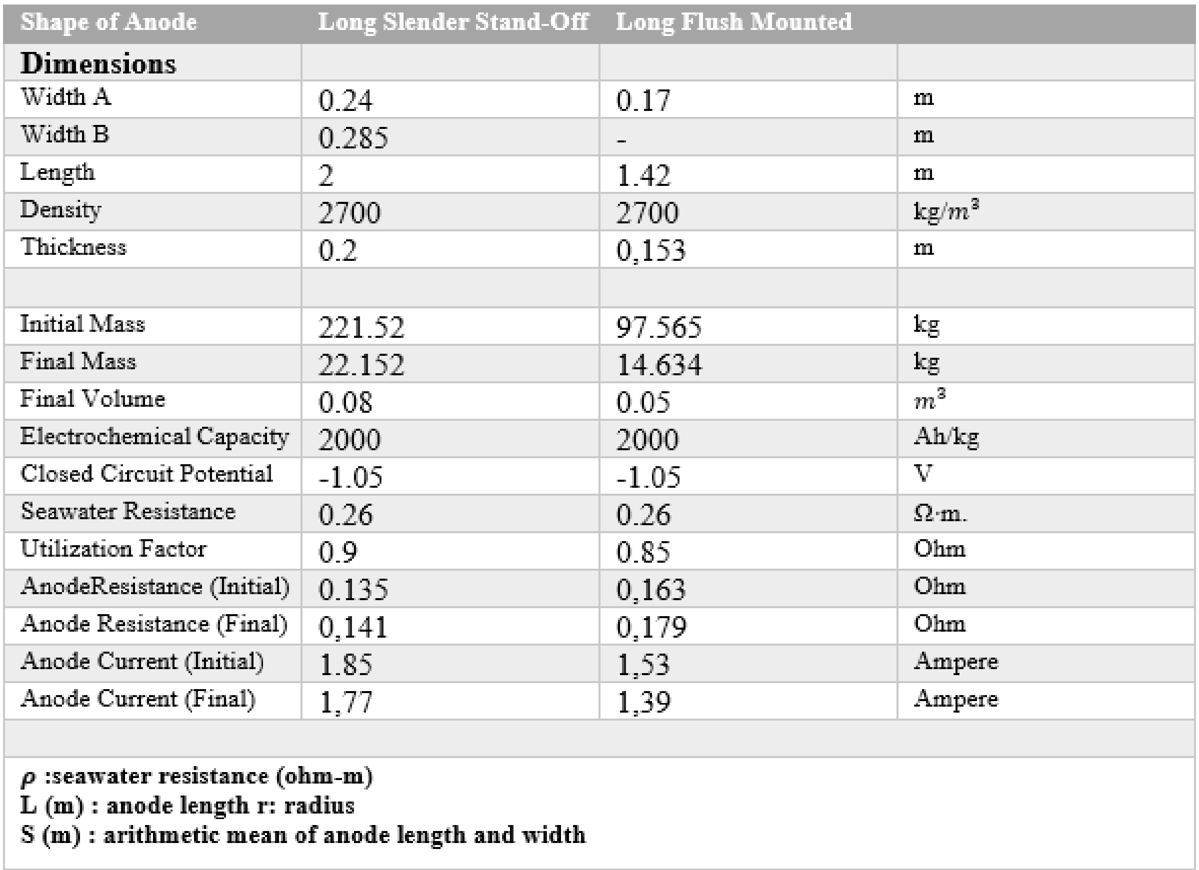
m_{ai}: Inıtial anode mass

u : Utilisation factor

This value of final mass along with anode density is used in the formula by which final volume can be obtained.

$$V_f = \frac{m_{af}}{I_a}$$

Finally, as the geometric shape will be changed afterward, the final shape of stand-off and flush mounted anodes can be assumed to be cylindrical.



Shape of Anode	Long Slender Stand-Off	Long Flush Mounted	
Dimensions			
Width A	0.24	0.17	m
Width B	0.285	-	m
Length	2	1.42	m
Density	2700	2700	kg/m^3
Thickness	0.2	0,153	m
Initial Mass	221.52	97.565	kg
Final Mass	22.152	14.634	kg
Final Volume	0.08	0.05	m^3
Electrochemical Capacity	2000	2000	Ah/kg
Closed Circuit Potential	-1.05	-1.05	V
Seawater Resistance	0.26	0.26	Ω·m.
Utilization Factor	0.9	0.85	Ohm
AnodeResistance (Initial)	0.135	0,163	Ohm
Anode Resistance (Final)	0,141	0,179	Ohm
Anode Current (Initial)	1.85	1,53	Ampere
Anode Current (Final)	1,77	1,39	Ampere

ρ :seawater resistance (ohm-m)
L (m) : anode length r: radius
S (m) : arithmetic mean of anode length and width

Table 23. Anode Calculations for Uncoated Structure

Discussion

The long period situation of offshore structures depends on the design and application of cathodic protection systems. Calculations of anode properties for the external surface of a hypothetical construction to be placed in 30 meters of water off the Canary Island are obtained for each coating category and uncoated structure in accordance with DNV – RP- 401. Stand-off and flush mounted anode shapes are used for the SACP system in order to protect throughout 25 years of design life and total currents to be calculated must be greater or equal than the mass needed for design lifespan. Mass of anode needed for stand-off shaped uncoated CP system is 108732.2 kg, it could be lowered to 104851.1, 44391.3, 22015.5 kg with the use of CAT I, CAT II, or CAT III coating. According to these anode mass results, it can be obviously observed the critical effect of coating in terms of use of anode mass compared to the uncoated structure. For flush mounted, uncoated mass is 115128.3 kg and it could be lowered to 111018.8, 47002.5, or 23310.6 kg with the use of CAT I, CAT II or, CAT III coating by means of DNV guide. Although there is no big difference in terms of anode mass, the stand-off anode shape is slightly more advantageous than the flush mounted anode shape. Hence, stand off shapes will be selected for designing and calculations for coating categories are provided in Table 24.

In order to obtain the number of anodes, current capacity along with mean current demand, year of design life and total hours of the entire year are utilized. Based on these parameters of stand-off shape obtained in table 24, required anode number for 25-years design life uncoated structure is 490. If coating is applied, it could be lowered to 170 by using category III coating.

Dimensions	Uncoated	Coating I	Coating II	Coating III	
Length	2	1.6	1.188	1.55	m
Width	0.26	0.198	0.175	0.187	m
Thickness	0.2	0.166	0.151	0.153	m
Initial Mass	221.52	147.56	96.236	129.875	kg
Final Mass	22.152	14.756	9.623	12.987	kg
Final Volume	0.08	0,05	0,03	0,05	m^3
Anode Resistance (Initial)	0.027	0,031	0,036	0,031	Ohm
Anode Resistance (Final)	0.029	0,032	0,038	0,033	Ohm
Anode Current (Initial)	9,26	8,06	6,94	8,06	Amp
Anode Current (Final)	8,62	7,81	6,57	7,57	Amp
Number of Anodes	490	710	461	170	
Mass of Anodes	108732.32	104851.1	44391.3	22015.5	kg

Table 24. Calculations based on Long Slender Stand-off anode

Due to variability of system regions, especially for the complex system, some parts might be poorly shielded while other parts might be overprotected. Hence, anode distribution is extremely important to be able to provide full protection over the system. Essentially, it’s not easy to obtain full protection due to installation issues. In addition, the lower amount of coating layers is preferable for the poorly protected regions not to affect more the anode distribution. For instance, the transition piece is one of the problematic areas in terms of anode distribution. If the uncoated design is considered, the surface area is exposed to more layers due to the high amount of anode number. But if CAT III coating is applied, 170 anodes will be employed instead of 490. Hence, a lower amount of layer will be used and anode distribution will be less affected from layers.

When the electricity leaves the anode into seawater in order to provide steel protection, a potential difference occurs. This situation may cause a problem due to insufficient polarization for a certain distance in which too far away from anode in terms of corrosion prevention. Therefore, design calculations must be provided carefully and results obtained from calculations must be followed in order to avoid insufficient distribution of anode and current weakness. Concerning to ICCP and SACP designs, it’s easier to provide convenient design calculations for ICCP systems due to no necessity of finding the sufficient anode mass to obtain electricity for the design lifespan as it does in SACP systems. Also, the use of dielectric isolation between cathode and anode in ICCP and having a high voltage that comes from the DC power source results in an effective solution in terms of distribution. For SACP systems, Mohamed A. El-Reedy (2012) has emphasized the importance of anode shapes by giving an example between flush mounted and stand off anode. Based on this example, despite anode mass to be applied will be the same for both anode shapes, better current output and hence, the better current distribution is obtained from stand off anode. Having a greater utilization value is also the positive factor for stand off anode (For stand off : 0.90, for flush mounted 0.85). In addition, optimization methods analyzed with Boundry Elements Technology (BEM), a numerical technique that is used for modeling, is also a good manner for determining of anode locations for CP systems in order to achieve better potential distribution [47]. Before installation, a boundary element analysis system (BEASY) can be added into the CP process and helpful results for the effectiveness of anodes to be placed into the system can be evaluated as it applied in (Z Shamsu, 2011- SIMULATION OF GALVANIC CORROSION USING BOUNDARY ELEMENT METHOD)'s experiment.

According to results, it can be noted that there is no change between uncoated and Category I in terms of current demand results except a little change existed in mean current demand. In contrast, an obvious benefit can be obtained by using Category II or Category III coating in current demand. The main reason why current demand has a lower result in Cat II and Cat III is the value of the cathodic breakdown factor. According to DNV RP 401, the coating breakdown factor can reduce current demands by approximately 80% when “good coating” is applied [37]. Also according to anode mass results, there is little reduction occurring in Cat I whilst, Cat II and Cat III have severe reductions.

Current densities are provided by following the DNV RP B401 recommendation in Table 17. DNV refers that current densities obtained in this table are defined based on water climatic regions and water depth. According to current densities shown in Table 6.1. in (Singh, Corrosion Control for Offshore Structures, 2014), current densities for the related zone are 0.150,0.070 and 0.090 for initial, mean and final density [49]. As DNV recommendations are greater than these values, greater current demands are obtained, hence, better protection is provided in this experiment. With this approach, ISO standards can also be used for other offshore structures (e.g. ISO/DIS 23221 is used for pipelines).

As the design lifespan of the system is considered to be 25-years and therefore long-term corrosion loss is observable, the material should be selected based on time and selected material should meet an efficient tolerance against fatigue damage. The majority of wind turbine monopile systems are made of S355 steel. The optimization and cost-effective design of extra-large wind turbines will be aided by a thorough understanding of their corrosion-fatigue properties and precise steel selection [51]. The best understanding of fatigue throughout design lifespan can be obtained by testing [52]. Based on this data received from testing, maintenance should be done regularly in order to avoid failure. The other corrosion-fatigue problems may happen due to environmental conditions, such as marine growth which may result in microbially induced corrosion.

As the system will be designed in a subtropical region, higher temperatures and also humidity will be observed throughout design life. Hence, monitoring offshore wind turbines is particularly important. All the data received from monitoring systems should be recorded on a daily note.

Magnesium or zinc could be selected for the anode type of the system. However, due to its higher electrochemical capacity, lower weight and economic benefit, the aluminum anode was selected. Aluminum will become passive faster compared to zinc or magnesium and thus lowering the current output. Therefore, mercury, gallium or, indium can be used as an alloy for aluminum in order to avoid passivation [29]. In addition, the amount of anode will decrease by using coating and it’s quite significant in terms of the environmental aspect.

Concerning to environmental aspect, coated design selection is also desirable. Over the lifespan, cathodic protection induces anode dissolution and this anode leads to marine sediments and water pollution. According to (C. Rousseau)’s study, providing information about mobility of zinc anode in marine sediments, a high amount of zinc anode concentration was observed in the seawater and also surface sediments due to anode dissolution. And then, existing sediments also create secondary pollution since zinc anodes can be mobilized again by seawater [53]. Whereas, the case study of (C. Gabelle a), providing information about the dissolution of Aluminum anodes, shows that while anodic dissolution did not significantly raise the concentration of Aluminum in the seawater, sediments tested near the sacrificial anodes revealed both enrichment and an increase in Aluminum mobility [54]. Therefore, aluminum is not only a good selection in terms of its electrochemical capacity and low weight, it's also would be a better selection in terms of less pollution compared to the zinc anode. While coastal waters generally have an aluminum concentration of 0.5–0.68 g/, zinc concentration is as high as 4 µg/L and more.

The best locations to exploit the off-shore wind source in Canary Island, regarding to Martin Mederos et al. (2011), González et al. (2017), and Schallenberg-Rodrguez and Garca Montesdeoca (2018), are the area between Tenerife Island and the west-northwest coast side, as well as the south and southeast parts of the island. Concerning to permission, the implementation of offshore wind farms are supported by Asociación Empresarial Eólica (AEE) and a CP design for 4 assembled wind structure can be considered in this experiment. If an uncoated structure that has 108 tonnes of anode mass based on DNV calculations is planned for per structure, the total amount of aluminum consumed in the system will be 532 tonnes for each structure. By using Coating III, it could be reduced to 88 tonnes.

Conclusion

Sacrificial cathodic protection design calculations of hypothetical offshore wind system located in Canary Island is obtained by means of DNV guidance. Relevant initial parameters (seawater parameters, initial mass, length, thickness, etc.) have been obtained from related offshore website sources and previous researches about CP design calculation. On this basis, it can be observed that initial parameters are required for designing cathodic protection of an offshore system and getting a valid result is available.

The intention of these calculations is to determine the differences between coated and uncoated structure in terms of anode and mass requirement. According to the results, it's obvious that the use of Coating II or Coating III would provide severe benefits in terms of current demand reduction, anode requirement and total mass of anode. This beneficial effect will minimize anode consumption and expense, as well as aluminum emissions, and will lead to a more suitable anode distribution in order to provide that Cathodic Protection is deployed across longer distances due to lower IR drop.

As a result, corrosion risk can be lowered by using coating in combination with cathodic protection and design calculations prove this approach. Although the coating is quite an effective method, other factors should also be taken into account. For example, stand-off anode has a better result in the use of design calculation but considerations may be given in order to provide better resistance. Also concerning to environmental factors, materials that decrease the risks of the environment by means of applying corrosion inhibitors, changing the chemical reactions, avoiding sea pollution, shifting the temperature or velocity, etc. can be taken into account. Finally, one of the most important factors is anode distribution. Therefore, providing a better distribution and combining the different zones to reach every place is the major point of cathodic protection design.

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