

The University of Akron IdeaExchange@UAkron

Honors Research Projects

The Dr. Gary B. and Pamela S. Williams Honors
College

Spring 2016

Corrosion Protection Systems in Offshore Structures

Hristo Ivanov

University of Akron, h.ivanov10@gmail.com

Please take a moment to share how this work helps you [through this survey](#). Your feedback will be important as we plan further development of our repository.

Follow this and additional works at: http://ideaexchange.uakron.edu/honors_research_projects

 Part of the [Civil Engineering Commons](#), [Ocean Engineering Commons](#), [Other Engineering Commons](#), and the [Structural Engineering Commons](#)

Recommended Citation

Ivanov, Hristo, "Corrosion Protection Systems in Offshore Structures" (2016). *Honors Research Projects*. 281.
http://ideaexchange.uakron.edu/honors_research_projects/281

This Honors Research Project is brought to you for free and open access by The Dr. Gary B. and Pamela S. Williams Honors College at IdeaExchange@UAkron, the institutional repository of The University of Akron in Akron, Ohio, USA. It has been accepted for inclusion in Honors Research Projects by an authorized administrator of IdeaExchange@UAkron. For more information, please contact mjon@uakron.edu, uapress@uakron.edu.

Corrosion Protection Systems in Offshore Structures

HRISTO IVANOV

ABSTRACT:

Corrosion plays a pivotal role in the engineering world. Engineers of all disciplines must consider the dangers that this phenomenon can incur. Interestingly, corrosion mitigation is not a topic that is addressed in most academic curricula. The goal of this paper is to give engineering students a brief introduction into corrosion and some of the prevention techniques commonly used today.

The design of a corrosion protection system for offshore structures is discussed in order to illustrate how these techniques can be utilized even in the most extreme environments. First, the driving force behind corrosion is examined, introducing the basic mechanics that fuel this phenomenon. Some of the most common types of corrosion experienced by structures are discussed to make engineers aware of what to expect in the field. Next, the most widely used corrosion mitigation techniques such as coatings and cathodic protection are addressed. Utilizing currently recommended industry practice, an in-depth discussion of the process of designing a cathodic protection system for offshore structures is studied. Finally, this procedure is demonstrated by applying the design process to an existing offshore structure.

Table of Contents

Introduction – Basics of Corrosion.....	1
General Corrosion.....	2
Localized Corrosion.....	2
Galvanic Corrosion.....	3
Environmental Corrosion Cracking.....	4
Corrosion Protection Systems.....	5
Cathodic Protection.....	5
Impressed Current Cathodic Protection Systems (ICCP).....	7
Sacrificial Anodes (Galvanic Action).....	8
Protective Coatings.....	9
Cathodic Protection Design for Offshore Structures.....	11
Identify Zones and Surface Areas.....	11
Determine the Potential.....	12
Current Density and Demand.....	13
Current Drain.....	13
Anode Calculations.....	14
Design of a Monopole Structure.....	15
Conclusion.....	18
References.....	19
Appendix A – DNV-RP-B401 Tables & Figures [10].....	A-1
Appendix B – Excel Spreadsheet Calculations of Cathodic Protection System of Submerged Zone.....	B-1

List of Figures

Figure 1	1
Figure 2	6
Figure 3	6
Figure 4	7
Figure 5	8
Figure 6	9
Figure 7	10
Figure 8	10
Figure 9	11
Figure 10	12
Figure 11	15
Figure 12	16

List of Tables

Table 1	2
Table 2	3
Table 3	17
Table 4	17
Table 5	18

Introduction – Basics of Corrosion

The inventions of man have been in a constant struggle with the forces of nature for a very long time. Corrosion can be described as nature's attempt to return those inventions back to their natural state. A more formal definition describes it as the deterioration of a metal that results from an electrochemical or chemical reaction to its surrounding environment [1]. In order to truly understand this process, it must first be analyzed at a microscopic level. For the chemical reaction to occur, a corrosion cell comprised of four components must be present. An active corrosion cell is defined as containing the following [2]:

1. An anode (the location from where electrons are emitted and metal loss occurs).
2. A cathode (the location where electrons collect).
3. A metallic path (often the structure itself provides that metallic path).
4. An electrolyte, in which the anode and cathode are immersed (the electrolyte could be any moist surface or immersion in any conducting fluid, water, or soil).

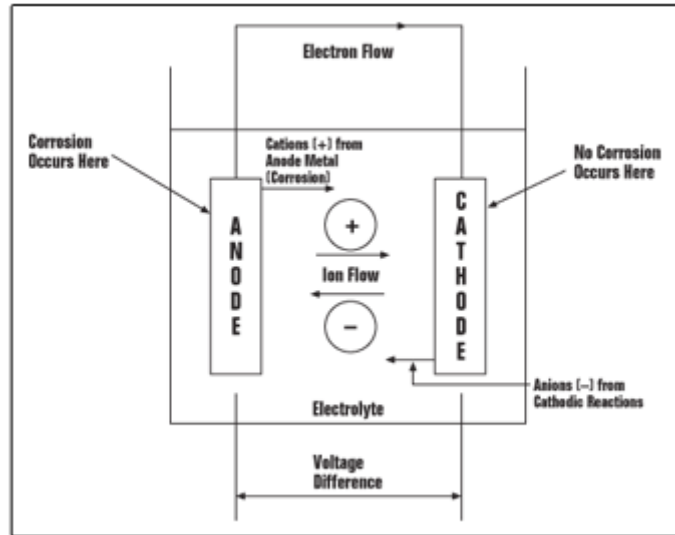


Figure 1 - Corrosion cell explaining the relations of the four key components of an active cell [3].

As shown in Figure 1, the four components form a circuit and allow a corrosive chemical reaction to occur. Due to a difference in electrical potential, electrons flow from the anode towards the cathode along a metallic path. In the presence of an electrolyte (water in this case), there is also an exchange of ions where negatively charged particles called anions flow towards the anode while positively charged ions called cations flow towards the cathode. These four components complete the corrosion cell and cause the anodic material to deteriorate (metal loss). At its core, the concept seems simple, but when looking at the overall picture, one will realize corrosion is a highly complex process that is both caused and affected by many factors. It is therefore important to begin by first understanding the different forms corrosion can take.

General Corrosion

General corrosion is the most simplistic of the forms. It refers to the rate at which a metal uniformly corrodes, creating byproducts commonly referred to as rust and causing thinning of the material. In order to better understand and control general corrosion, engineers have given measurable units to this rate. The most commonly used are mil per year (1 mil = 0.001 in), millimeters per year, or inches per year. Table 1 provides an example of how the different rates of corrosion can be categorized to relate to the acceptable uses of materials in the physical world. NACE (National Association of Corrosion Engineers) has a similar classification where the ranges of rates are divided into four levels. Overall, general corrosion is recognized as being tolerable, since the metal loss can relatively easily be controlled by the common corrosion protection techniques applied today.

Table 1 - Corrosion rate ranges categorized by their performance and applications [4].

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 impellers)
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

Localized Corrosion

Unlike general corrosion, localized corrosion refers to the deterioration of specific areas of a surface while the rest of the surface corrodes at a much slower rate [5]. This behavior is primarily caused by the environmental conditions of the exposed material. Localized corrosion can be categorized as pitting, fretting, cavitation, crevice, and filiform.

Pitting is described as a hole or cavity that occurs in a localized corrosive area of a material. Perhaps the most common way pitting is initiated is by the electrical circuits that are created through the impurities of metals [2]. Furthermore, any breaks in the protective coating or passive film of the material are additional causal factors. This is a dangerous form of corrosion that is not easy to detect as the corrosion byproducts often cover the pit, also making it difficult to determine its depth.

Fretting is another form of localized corrosion which is the result of unintentional mechanical contact between two surfaces. This contact is commonly induced by vibrations between two highly loaded surfaces [5]. As a result, the unintended contact of the surfaces causes the removal of protective film, therefore exposing them to the corrosive nature of the respective environment.

Crevice corrosion can be categorized as the result of “the potential difference in the concentration of materials inside and outside the crevice, often as a result of a design flaw that restricts the free flow of the environment between the surfaces” [2]. For instance, a situation where this may occur is when water can infiltrate a tight, narrow space (crevice) between two steel plates. The water inside the crevice has lower oxygen levels, causing the metal surface in contact with it to become anodic while the


portion of the metal surface in contact with the water outside the crevice has higher oxygen levels and becomes cathodic, initiating the corrosion process. In the inspection of bridges, this type of corrosion is commonly referred to as pack rust.

Filiform is actually a type of crevice corrosion where microscopic defects of a protective coating are breached, leading to formation of corrosion product underneath the coating [2]. Similarly, this can also be attributed to the difference in oxygen levels which cause the formation of cathodic and anodic areas.

Galvanic Corrosion

Galvanic corrosion is initiated by the presence of an electrical cell reaction described earlier. In this type of corrosion, the four essential components are readily available and an electrical current can be facilitated quite easily. As mentioned previously, metals containing impurities can form an electrical circuit where electrons can flow from one spot to another within that same metal surface, causing corrosion. Consequently, purified metals are valued more highly since they have a greater resistance to corrosion. This flow of energy can also be exemplified when referring to the difference in potential between types of metals. Table 2 contains a list of common metals in order from those with more positive potential (Noble) to those with more negative potential (Active).

Table 2 - Galvanic series

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)	

Noble metals refer to metals extracted from the earth that are usable in their natural state. On the other hand, active metals are those that, once extracted, require additional energy to be converted into a usable form. This is an important corrosion concept that is commonly observed in the engineering world. For instance, consider a titanium object connected to an object made of zinc. Electrons will flow away from a higher energy state (negative) towards a lower energy state (positive) [2]. From the galvanic table, the zinc object has a more negative potential and will therefore act as an anode while the titanium object will act as the cathode. The metallic path is already present and an electrolyte as simple as atmospheric moisture can complete the electrochemical cell and initiate the reaction. The rate of corrosion is then based on how far away zinc is from titanium in the galvanic table. The farther away

two materials are from each other in the table, the higher their potential difference, which means a faster rate of corrosion.

An important aspect of galvanic corrosion concerns the ratio of surface areas between the anode and cathode. This ratio, coupled with certain conditions, can dictate the rate of galvanic corrosion between two metals. For instance, an anode that is smaller than a cathode will corrode faster in immersed conditions [2]. Consequently, an inverse relationship is observed where the closer the anode area comes to the cathode area in size, the slower the rate of corrosion will be. Once the anode area becomes larger than the cathode area, the corrosion is deemed negligible [2]. Therefore, a small anode/cathode area ratio is undesirable as it will lead to rapid, concentrated deterioration of the anode. This concentration most often occurs at sharp points and edges in a cell's geometry.

Environmental Corrosion Cracking

In the presence of corrosive environments, specimens can form cracks when subjected to tensile forces at stress levels much lower than their strength capacity. These environmental cracks consistently form at 90 degrees from the tensile force and are caused by the contribution of numerous factors such as temperature effects and residual stresses from welding or machining [5]. This ultimately leads to advanced crack propagation that, combined with a corrosive environment, results in a brittle failure. Some of the most common forms of environmental corrosion are stress corrosion cracking (SCC), corrosion fatigue, and hydrogen embrittlement.

The description of stress corrosion cracking is very similar to the general definition of environmental corrosion. It is used to describe the premature failure of a material when subjected to tensile stresses under corrosive conditions. This type is actually considered one of the most dangerous forms of corrosion [5]. This is mainly due to the fact that these cracks form at the microscopic level, making them extremely difficult to detect during inspection. Additionally, there is little consistency between studies of SCC failures, implying that they are very hard to predict and can be unexpected.

Much like regular fatigue, corrosion fatigue results from stresses caused by repeated loading and unloading over time. The key difference is the introduction of a corrosive environment, which significantly lowers the expected failure stresses and failure times. In fact, the security of defined limit states is eliminated due to the varying ranges of corrosion damage caused by the environment that accelerates the chance of failure [5].

Hydrogen embrittlement failures are caused by the presence of a tensile loading onto a metal containing dissolved hydrogen. It is known that hydrogen induced into a metal causes significant negative effects such as reduced ductility, reduced strength capacity, and cracking [5]. Again, this can lead to failures at stresses much lower than expected. Although the detection of this phenomenon is not thoroughly understood, evidence has shown that this type of corrosion is mostly experienced by metals with high yield stresses. The formation of hydrogen can result as a by-product of a cathodic reaction where water acts as the reactant instead of oxygen. In cathodic protection systems, this can be initiated when the electric potential of a metal is lowered to a certain level where the created alkali environment triggers the hydrogen evolution.

Corrosion Protection Systems

As mentioned before, corrosion is a highly complex process that is dependent on multiple factors. Fortunately, advancement of certain technologies have helped scientists better understand corrosion and develop ways to control and even eliminate it when possible. Today, there are five distinct approaches to corrosion control:

- No protection (wastage allowance)
- Protective Coatings
- Cathodic Protection of Bare Steel
- Cathodic Protection of Coated Steel
- Corrosion Resistant Metallic or Plastic

In offshore structures, it is not uncommon to utilize a combination of several approaches to address corrosion problems in different areas of the structure.

Cathodic Protection

Perhaps one of the most common corrosion protection techniques used today is known as cathodic protection. The first practical application of this method was used in the 1820's by Sir Humphrey Davy to mitigate the corrosion of copper sheeting on naval vessels [6]. Following the success of Davy's prototype, cathodic protection quickly developed alongside the emerging oil and natural gas industry at the time and has now become a widely used technique.

The concept of how cathodic protection (CP) works is ingeniously simple. It stems from the basic theory behind corrosion, the active corrosion cell. Having all four components present allows the electrochemical reaction to occur, resulting in electrons flowing from the anode to the cathode and causing corrosion of the anodic material. The theory behind cathodic protection is to supply enough electrons to the anodic area that it becomes cathodic, thus slowing down or eliminating deterioration of the anode altogether. This is done through the use of an external anodic material that supplements the supply of electrons to the area in danger. Figure 2 below is a polarization diagram, which is a graphical representation of some of these principles. Plotting the electric potential of a metal (E) against the log of the anodic and cathodic reaction rates in the form of current densities (I) demonstrates how cathodic protection works in a quantitative manner. The intersection of the anodic and cathodic curves is defined as the electric potential (E_{corr}), where the anodic and cathodic reaction rates are equal and corrosion occurs naturally. Once the protection system is properly set and electrons start flowing towards the metal, the rate of the anodic reaction becomes insignificant at potential E_1 . At potential E_1 , the rate of the cathodic current is increased to I_1 , which is also considered the amount of current needed to be supplied by the system in order to maintain the corresponding potential. This results in the metal becoming "cathodically protected" since the rate of deterioration is kept at an absolute minimum value. If the current were to be increased to I_2 , it can be seen that the corresponding potential (E_2) would not yield a lower rate of deterioration. Consequently, this scenario of over-protecting the metal should be avoided since the extra current supplied from the system is essentially wasted.

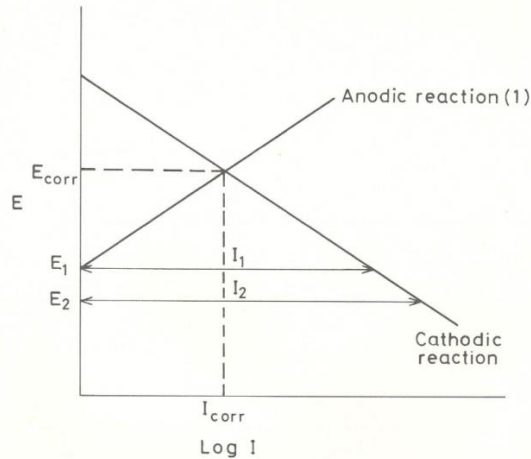


Figure 2 – Cathodic protection explained by a polarization diagram showing how changing the kinetics of each reaction mitigates corrosion [6].

The theory seems simple enough, but once put into practical use, it becomes evident that certain modifications need to be made. Figure 2 above displays the corrosion reactions with the assumption that all reactants are readily available. In the natural environment, it is known that the most common cathodic reactant is oxygen [7]. Additionally, it is also known that oxygen does not mix particularly well with aqueous solutions such as cool seawater. Consequently, the supply of oxygen becomes the limiting factor in the cathodic reaction due to its rate of arrival at the metal surface. Figure 3 represents how the polarization diagram must be modified to account for this. It can be seen that the cathodic reaction rate does not follow the kinetics described in Figure 2. In Figure 3, a maximum rate of cathodic reaction is reached when oxygen is being consumed as soon as it reaches the metal surface. The corresponding current required to achieve cathodic protection decreases significantly, but there are also other factors that must be considered. For instance, an increase in flow velocity will result in an increase in supply of oxygen to the metal surface. In turn, this will shift the maximum cathodic reaction rate to the right, therefore requiring more current in order to maintain protection.

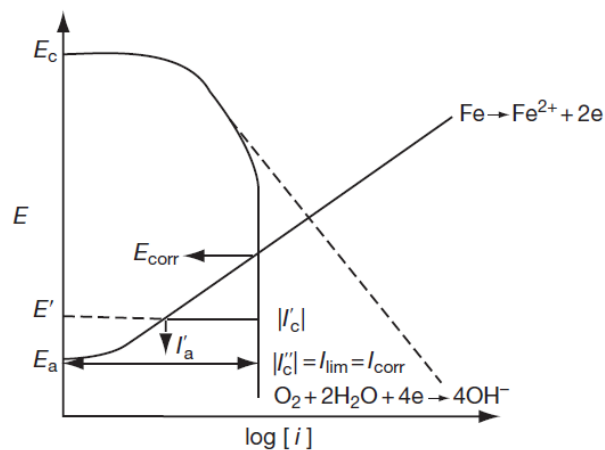


Figure 3 – Polarization diagram showing how the cathodic reaction becomes limited due to the supply of the reactant (oxygen) in an aqueous solution [7].

As the potential is lowered to achieve proper protection, another factor may also contribute to current demand. For instance, in neutral solutions, water can become the cathodic reactant, resulting in the

formation of molecular hydrogen [7]. Figure 4 shows the role hydrogen evolution plays in the polarization diagram. In order to sustain proper cathodic protection at a certain potential, the current supplied must be enough to maintain both oxygen reduction and hydrogen evolution reactions at the corresponding potential. Figure 4 shows that at a certain potential, hydrogen evolution can actually become the dominant factor in determining the current required.

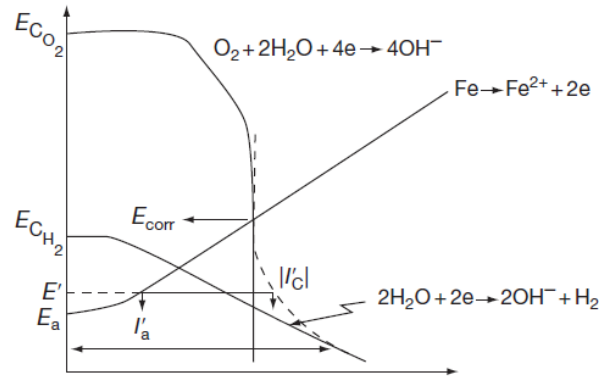


Figure 4 – Polarization diagram illustrating both types of possible cathodic reactions. At low electric potentials, current density is increased in order to sustain hydrogen evolution [7].

Furthermore, an over-protected structure with an excessively low negative potential can incur additional problems. Some of the issues that arise from the creation of an alkaline environment at the cathode are listed below [6]:

- Hydrogen embrittlement of steel
- Accelerated corrosion of lead and aluminum
- Loss of paint film/disbanding of insulating coating

Clearly, it is evident that both potential and current supplied are key factors that must be controlled in order for a structure to be cathodically protected.

Impressed Current Cathodic Protection Systems (ICCP)

Cathodic protection is applied to a structure through the use of either of two principal methods, impressed current or sacrificial anodes. Impressed current is discussed first and differs from the latter in that it creates an electrochemical cell that is driven by an external power supply. The basic components required to achieve this circuit are a power source, an electrode, an electrolyte, and the structure in need of protection. Figure 5 illustrates the components that comprise this circuit. The DC power source supplies the electrode with positive current which is then transferred onto the structure ionically and returns back into the power supply. It is important to note that this can only be achieved if the electrode and structure are both in contact with the electrolyte and are also connected electronically in order to complete the circuit [7].

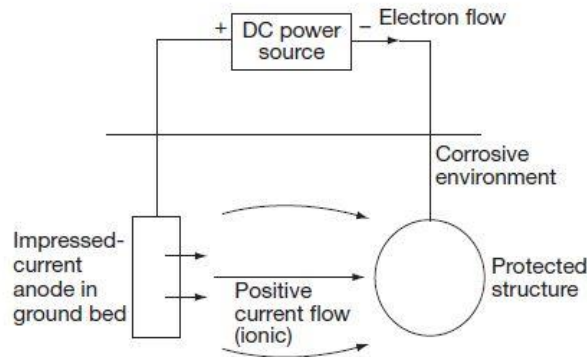


Figure 5 – Typical components of an impressed current cathodic protection system (ICCP) [7].

Since the structure and corrosive environment (electrolyte) will essentially remain constant, the focus of design is mainly around the power source and the electrode. In most scenarios, the power source will often be supplied through a connection to a main grid. In cases like offshore structures, alternative sources such as gas engines, renewable energy, or thermoelectric generators will need to be utilized. Lastly, the designer will need to choose the size, shape, and material for the electrode in the circuit. Relating back to how cathodic protection works, this electrode will act as the anode in the system and will therefore be the object that will deteriorate in order to protect the structure. Due to the nature of the impressed current method, corrosion of the anode is highly undesirable because resistance of the circuit is increased as the anode dissolves [7]. In other words, current flow to the structure will become disrupted by the increased resistance caused from the deteriorating anode, and proper cathodic protection will not be achieved. Consequently, the chosen material of the electrode needs to be heavily resilient to the anodic reactions that result from the impressed current. As mentioned before, since noble metals occur naturally, they have a lower energy state (positive potential) and are therefore very resistant to corrosion. Platinum would be an ideal material to use, but due to its cost is substituted by more feasible options such as platinized titanium or tantalum. Since these metals actually decompose the surrounding aqueous environment rather than themselves, they must also be chemically resistant to their own by-products (acid and chlorine) [7]. As a result, considerations of electrode placement and surrounding environments must be made. The advantage of using the impressed current method lies in its ability to drive high voltages, allowing a single anode placed remotely to protect large areas of a structure [6].

Sacrificial Anodes (Galvanic Action)

Unlike the impressed current method, the use of sacrificial anodes does not require an external power supply. Instead, it utilizes the natural tendency of electron flow from negative to positive potential to drive the current. This phenomenon was described earlier in the form of galvanic corrosion; therefore sacrificial anodes are often referred to as galvanic action. As shown in Figure 6, electrons are supplied to the protected structure by the anode via an electrical connection. Reactions at the anode driven by the environment produce metal ions that then act as positive current that flows towards the structure to complete the circuit. In practice, the anode is commonly mounted on a steel core and attached directly to the structure [7].

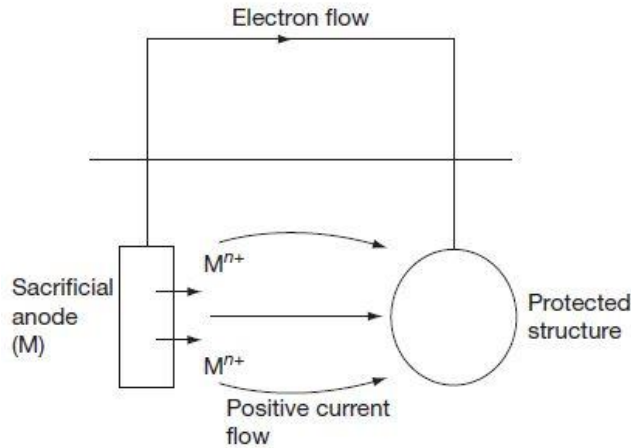


Figure 6 – Typical components of a sacrificial anode (galvanic action) cathodic protection system [7].

Another major difference between the two methods of cathodic protection is the choice of anode. In impressed current, the use of noble metals was desired in order to resist the high current provided by the power supply. In galvanic action, the opposite is true. Since the current is driven by natural potential difference, it is necessary for the structure to have a more positive potential so it can act as the cathode. Consequently, an anode material with a low negative potential such as magnesium, zinc, or aluminum is desired to ensure proper electron flow. In order to protect the structure over its entire design life, it is important to prevent passivation of the sacrificial anode. This results in the anode forming a non-conductive film on its surface which loses its activity and prevents it from supplying further current [6]. To prevent passivation, common industry practice is to control the quality of the material by reducing impurities as much as possible as well as alloying with elements such as indium [6].

Protective Coatings

Protective coatings have always been a pivotal part of corrosion mitigation. This is because coatings can be applied to almost any material and can protect it under virtually all environmental conditions. Typically, these systems are categorized into three different types: barrier, sacrificial, or inhibitive. Barrier coatings prevent the electrolyte from coming into contact with the substrate. If no electrolyte is present, the corrosion cell cannot be active since it is missing one of its four main components. However, if any part of this layer is breached, the difference in potential between the coating and substrate may cause accelerated local corrosion [8]. In order to mitigate this, inhibitor coatings are applied, which help suppress the rate of corrosion by shifting the anodic and cathodic reaction curves to the left. Figure 7 illustrates how the application of inhibitors affects the kinetics, ultimately resulting in a lower current density and a possible reduction of the rate of corrosion.

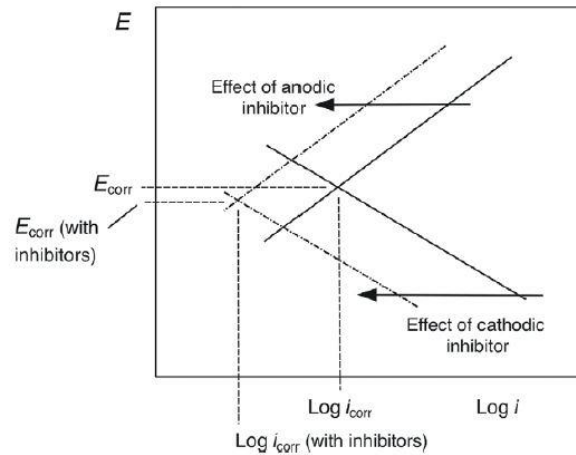


Figure 7 – Polarization diagram showing the effects on reaction kinetics when using anodic and cathodic inhibitors [8].

Sacrificial coatings are applied to protect the substrate through self-consumption. For instance, consider steel that has been galvanized, which means it is dipped and covered in a layer of zinc. The zinc coating then acts as a protective layer to the steel by sacrificing itself. Again, this process can be explained through the use of corrosion kinetics. In Figure 8, the polarization diagram shows how galvanically coupling the zinc (A) with the less active steel (M) results in an equilibrated potential E_{galv} . At this potential, the anodic reaction of the steel is reduced to $i_{diss, M}$ and corrosion is essentially stopped. On the other hand, the zinc (A) increases its anodic reaction to i_{galv} and deteriorates more quickly. This process is the basis of the sacrificial protective coating.

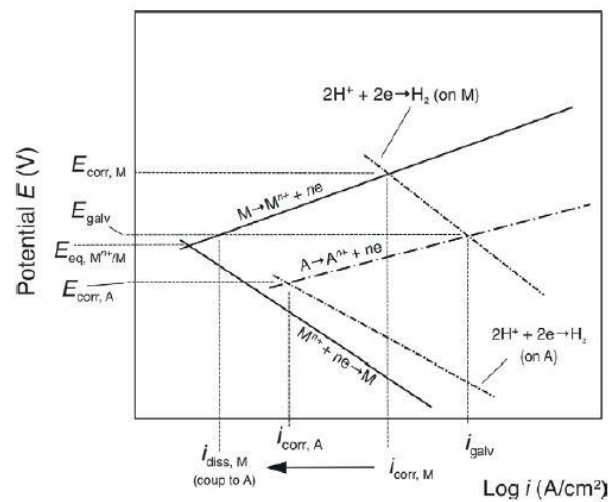


Figure 8 – Polarization diagram showing how sacrificial coatings protect the substrate by lowering the potential and current density [8].

Although a single layer of coating is adequate for many applications, there are instances where a coating system with multiple layers is required. As shown in Figure 9, the components of such a system can include a surface pretreatment, primer, undercoat, and topcoat. Like before, steel can be coated with a sacrificial zinc layer for cathodic protection. The addition of phosphate pretreatment and epoxy topcoat helps to suppress the corrosion of zinc and ultimately prolong the life of the protection system [8]. The

real advantage in this is that it can offer protection from a wide range of corrosion mechanisms. An important factor to consider for these systems is the compatibility between the different layers. Each layer's purpose should be to supplement the overall protection of the substrate without negatively affecting the adjacent protective coating layers in the system.

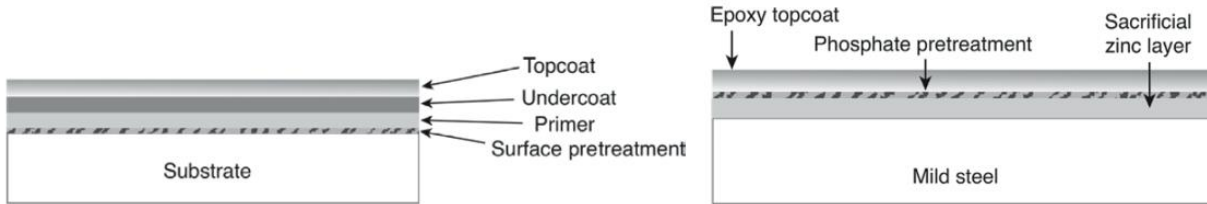


Figure 9 – (Left) Typical arrangement of a coating system with multiple layers. (Right) Illustration of an enhanced sacrificial coating system [8].

There are many different types of commercially available coatings on the market. In order to choose a suitable one, a designer must consider several factors such as the environmental site conditions, maintenance, application methods, and risk of damaging the coating during construction. Currently, organic zinc-rich primers, higher build epoxies, and polysiloxane coatings have shown great promise in reduced cost, increased performance, and ease of application in a wide range of environmental conditions [9]. Since coatings are an important part of corrosion prevention and structural failure, detailed documentation and procedures must be specified for every project. This should include information on relevant sections such as coating materials, surface preparation, coating application, maintenance, and repair.

Cathodic Protection Design for Offshore Structures

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

Identify Zones and Surface Areas

The design is initiated by first dividing the offshore structure into several sections or zones which will each require a different systematic approach. The three major zones are atmospheric, splash, and submerged.

The atmospheric zone refers to the section of the structure which is solely exposed to air. In other words, it is not affected by the change in tidal waves and therefore remains mostly dry and is not in constant exposure to an electrolyte. This zone does not require cathodic protection since a suitable coating system is enough to provide adequate corrosion control. Further design considerations include decreasing surface area through the use of tubular members, using connections that are less susceptible to crevice corrosion, and utilizing corrosion resistant materials as a substitute to steel [2].

The splash zone is the area between the atmospheric and submerged zones. This section becomes wetted by the constant rise and fall of the tide as well as the effects of ocean wind. As shown in Figure 10 below, the splash zone typically has the highest corrosion rate. Designers must therefore take special care in considering the type of protection system to be used. In most cases, utilization of a robust

coating system is a recommended practice. Cathodic protection is not often used in this area as it would be ineffective because the structure is not constantly in contact with an electrolyte in the splash zone, so the current supplied during this time would be wasted.

The submerged zone is below the splash zone and refers to part of the structure that is completely exposed to the electrolyte (seawater). This zone also exhibits significant corrosion rates that require special consideration as illustrated in Figure 10. Use of a high performance coating system supplemented with cathodic protection is highly desired to achieve full cathodic protection. Similarly, use of tubular members is preferred in order to avoid additional corrosion spurring from tight or recessed corners and crevices.

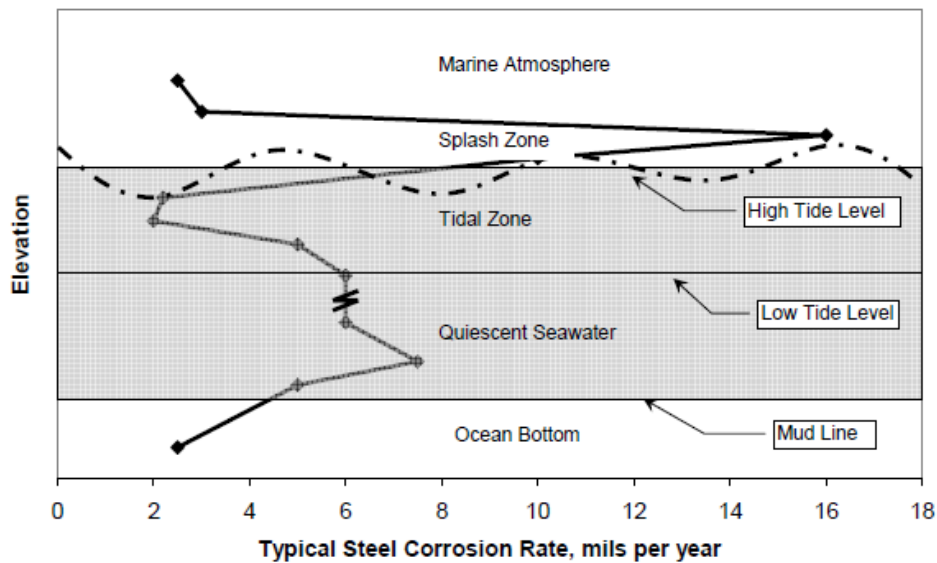


Figure 10 – Typical steel corrosion rates of each zone of an offshore structure [9].

The structure should also be further subdivided into areas based on factors like change in water temperature, coated vs. uncoated areas, and depth.

Determine the Potential

Determination of the correct potential that the CP system requires to maintain proper protection is another essential initial step. As previously discussed, there are many factors that affect the kinetics of the chemical reactions, which is why it is important to collect as much data as possible about the site specific environment. Generally, the range of optimum potentials is between -950 mV to -1000 mV with reference to a silver/silver chloride standard electrode [11]. Again, this value may vary based on the environmental conditions of the site. When looking up these criteria, it is important to note that potentials may also vary based on the standard reference electrode being used. Also, to reduce the chance of creating harmful alkali environments from hydrogen evolution, the designer should avoid choosing a very low potential value.

Current Density and Demand

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

When the structure is first immersed in the electrolyte, an initial current is needed to polarize the steel as quickly as possible [2]. This stage usually requires the highest level of current demand, which results from the initial high potential difference between the anode and cathode until polarization is achieved [11]. The final current density required refers to the stage of a structure's life when calcareous scales have formed on the surface of the metal in addition to marine growth. It is calculated in order to determine the amount of current needed to re-polarize the structure if those layers were removed or damaged due to periodic maintenance or storms [10].

The mean current density is also known as the maintenance current density. After polarization, the system will reach a steady-state potential significantly lower than the initial voltage required. Since cathodic polarization requires a relatively short time, this will become the required current density needed to maintain proper cathodic protection throughout the structure's design life.

A key value that must be calculated is the current demand (I_c) for each stage of a structure's design life. This demand is the product of the specific area to be protected (A_c), the relevant current density (i_c), and the coating breakdown factor (f_c) (if applicable), as shown in Equation (1).

$$I_c = A_c \times i_c \times f_c \quad (1)$$

Another necessary calculation is the current output of an individual anode which is based on Ohm's Law.

$$I_a = \frac{E_c - E_a}{R_a} \quad (2)$$

The current output of an anode (I_a) is equal to the difference in potential between the cathode (E_c) and anode (E_a) divided by the anode resistance (R_a) of the circuit. The resistance is dominantly controlled by the site-specific electrolyte environment and will therefore vary based on geographical location.

Calculating current densities is a difficult task since they are highly dependent on multiple factors and environmental conditions. In current practice, it is highly recommended to use the appropriate values in Table A-1 and Table A-2 of Appendix A for initial, mean, and final current densities. These values are considered conservative in order to account for variables such as the harsh weather experienced at sea [10]. More recently, there have been other novel approaches developed to help determine the current densities with the aim of optimizing anode size. The slope parameter method is one such approach that has been projected to reduce the anode mass of a typically-sized structure by 32% compared to the recommended practice described in this paper [12]. Additionally, another first-principles based method has been presented by Hartt and Lemieux [12] to help better predict and ultimately reduce the mean current density required for a structure.

Current Drain

Due to the nature of cathodic protection systems, they are very sensitive to outside interference. For instance, if temporary machinery is brought in the vicinity of the CP system, it will drain some of the current. Some of the most common sources include mud mats, piles, well casings, and mooring chains. Therefore, it is necessary to account for current drain by adding it to the required current demand. The

procedure to calculate the current drain demand is similar to the process described above. The design current densities will be the same as those found by using Appendix A.

Anode Calculations

Selection of the type of anode is another important step in the design process. The three major types of anodes are standoff, flush-mounted, and bracelet. Considerations that must be made are the structure itself, available attachment positions, and size needed to match current demand [2]. For offshore structures, it is common to attach long, standoff anodes weighing up to one ton. Based on this selection, the anode resistance, utilization factor, and electrochemical capacity can then be determined. The utilization factor describes the fraction of anode material that can be utilized to produce current over the design life [2]. According to the recommended practice by DnV, it is strongly advised to use the given values for electrochemical capacity in Table A-6 of Appendix A. Values provided by manufacturers are most likely based on short-term testing that is not representative of actual conditions nor effects caused by long term use [10]. The required anode mass (M_a) to maintain cathodic protection throughout the design life can be calculated from Equation (3) below:

$$M_a = \frac{I_{cm} \times t_f \times 8760}{\mu \times \epsilon} \quad (3)$$

where I_{cm} is the mean (maintenance) current demand for a section, t_f is the design life (years), μ is the utilization factor, and ϵ is the electrochemical capacity. The constant (8760) is used to convert the design life (t_f) into hours.

Additionally, the number of anodes required to produce such current must also be calculated.

$$N = \frac{I_c}{I_a} \quad (4)$$

In Equation 4, the number of anodes required (N) is equal to the current demand (I_c) from Equation 1 divided by the current produced by a single anode (I_a) calculated in Equation 2. The current demand should be checked for each stage, and the highest resulting number of anodes required will control. Given that the initial current is almost always the highest, it will likely be the governing value.

An important consideration that must be made during this step is the calculation of anode resistance. Table A-7 in Appendix A provides the necessary formulas based on the type of anode. This resistance must be determined at both the initial and final stages of the anode's life. At the initial stage, the original dimensions of the anode shall be used in the given equations. To obtain the final stage anode dimensions, the final anode mass must be determined by using the utilization factor in Equation (5).

$$m_{af} = m_{ai} \times (1 - \mu) \quad (5)$$

The final dimensions of the anode can then be calculated using the final net anode mass in conjunction with the specific density of the material.

Calculating the number of anodes for the mean (maintenance) current demand requires some slight modifications to the equation. Since the mean current demand to polarize the structure is significantly lower than the initial demand, Equation (4) is adjusted to incorporate variables such as design life and current capacity instead of anode output.

$$N = \frac{I_{cm} \times t_f}{C_a} \quad (6)$$

In Equation 6, the number of anodes (N) is equal to the mean current demand (I_{cm}) multiplied by the design life in hours (t_f) and divided by the current capacity (C_a). The current capacity can be calculated using the following equation.

$$C_a = m_a \times \varepsilon \times \mu \quad (7)$$

As a final check, the following requirements shall be met to satisfy the DnV Recommended Practice.

$$C_{a\ tot} = N \times C_a \geq I_{cm} \times t_f \quad (8)$$

$$I_{a\ tot\ i} = N \times I_{ai} \geq I_{ci} \quad (9)$$

$$I_{a\ tot\ f} = N \times I_{af} \geq I_{cf} \quad (10)$$

Design of a Monopole Structure

To demonstrate the procedure described above, the design of a cathodic protection system of an existing monopole offshore structure is discussed. This structure is located in a tropical region in Southeast Asia off the coast of Indonesia. The length of the entire monopole is approximately 60 meters. The topmost 10 meters of the structure exposed to the splash zone have a diameter of approximately 1 m that transitions into 1.5 m for the 50 meters that will be submerged.

Installation of offshore structures is a complicated process that requires careful coordination and efficiency. This is mainly due to the high costs associated with mobilization in offshore construction. As shown in Figure 11, sections of this structure such as the platform and monopole were first assembled onshore and then shipped to the site via barges.



Figure 11 - (Left) Platform assembled onshore. (Right) Monopole being transported to site. [Photos courtesy of Dr. Anil Patnaik, The University of Akron]

Figure 12 shows the finished offshore structure, which consisted of a platform containing a helipad along with some small living quarters that rested on the 60 meter long monopole.



Figure 12 - Finished monopole offshore structure after installation. [Photo courtesy of Dr. Anil Patnaik, The University of Akron]

The first step in the design of the corrosion protection system was to divide the structure into different zones. For simplicity, the structure was segregated by the atmospheric, splash, and submerged zones.

The atmospheric zone consists of the platform that contains the helipad and living quarters. As shown in Figure 10, this zone experiences fairly low corrosion rates and will therefore only require a simple coating system. Additionally, this area is perhaps the most accessible and will allow for periodic maintenance of the coating.

The splash zone covers the 10 meter length of the monopole with a 1 meter diameter on which the platform rests. As mentioned before, even though this area experiences the highest corrosion rate, use of a cathodic protection system would be inefficient as the area would not be in constant contact with an electrolyte. Instead, a multilayered, robust coating system or Cu-Ni sheathing must be implemented to mitigate the corrosion.

The submerged zone consists of the remaining area of the monopole structure that is under water. This area will be in constant contact with the electrolyte and will require use of cathodic protection coupled with a protective coating. Table 3 lists all the variables associated with the required current for the structure. The current densities obtained from Appendix A were used in conjunction with the coating factors and surface area of the submerged zone to calculate the current demand for each stage of the structure's life.

Table 3 – Basic design parameters of the CP system for the submerged zone.

Current Calculations		
Variable	Value	Notes
Surface Area	239.03 m ²	
Initial Current Density	0.12 A/m ²	Table A-1
Final Current Density	0.08 A/m ²	Table A-1
Mean Current Density	0.06 A/m ²	Table A-2
Initial Current Demand (Ici)	28.68 A	
Final Current Demand (Icf)	19.12 A	
Mean Current Demand (Icm)	8.61 A	

With the current demand now known, the next step is to select an anode to meet the design requirements. For this exercise, a commercially available anode from Deepwater (Type A148.0S1) was chosen. Following the recommended practice by DnV, some of the anode properties were derived from Appendix A instead of values provided by the manufacturer. Table 4 lists these properties along with a summary of the necessary anode design values. The goal was to determine the required number of anodes necessary to cathodically protect the submerged zone of the structure. As expected, the demand to polarize the structure during the initial stage controlled the overall number of anodes.

Table 4 – Summary of calculated anode variables pertaining to the design of the CP system for the submerged zone.

Anode Calculations		
Variable	Value	Notes
Design Life	20 years	
Anode Type	Al-based	
Electrochemical Capacity	2,000 A-h/kg	Table A-6
Utilization factor	0.9	Table A-8
Design Potential	-0.95 V	
Anode Potential	-1.05 V	Table A-6
Resistance (i)	0.065 ohm	
Resistance (f)	0.088 ohm	
Current Output/Anode (i)	1.55 A	
Current Output/Anode (f)	1.13 A	
Anode Mass Required	838 kg	
Current Capacity/Anode	30.41 A-hr	
Number of Anodes (i)	19 anodes	
Number of Anodes (f)	13 anodes	
Number of Anodes (m)	6 anodes	

Finally, to ensure that all the design requirements of the cathodic protection system are met, Table 5 lists the required criteria that was checked. The anode mass, mean capacity, and initial & final current demand were all greater than the required values. More detailed calculations of the cathodic protection design for the submerged zone can be found in Appendix B.

Table 5 – Comparison of the calculated anode values to the required design parameters for the submerged zone.

Criteria Check				
Criteria	Anode		Demand	
Anode Mass	2812 kg	≥	838 kg	OK
Mean Capacity	577.81 A-yr	≥	172.10 A-yr	OK
Initial Current Demand	29.40 A	≥	28.68 A	OK
Final Current Demand	21.56 A	≥	19.12 A	OK

Conclusion

Incorporating considerations for corrosion in the design process should be essential for almost all engineers. By first understanding how the phenomenon works, it becomes evident that corrosion is a process of the natural world that is not easily avoided. Knowing the different forms it can take then allows the designer to predict what type of corrosion might be expected based on the environmental conditions of the project. Most importantly, engineers must be made aware of how to properly mitigate the deterioration process through methods such as protective coatings, impressed current cathodic protection systems, and sacrificial anodes. Although these techniques were specifically discussed in relation to the offshore industry, their use can be extended to numerous other applications with various levels of corrosion risk.

References

- [1] L. Van Delinder and A. Brasunas, *Corrosion Basics, An Introduction*. Houston, TX: National Association of Corrosion Engineers, 1984.
- [2] R. Singh, *Corrosion control for offshore structures*. Waltham, Massachusetts: Gulf Professional Publishing, 2014.
- [3] *NACE International Basic Corrosion Course Handbook*. Houston, TX: National Association of Corrosion Engineers, 2000.
- [4] H. Uhlig and R. Revie, *Corrosion and Corrosion Control: An Introduction to Corrosive Science and Engineering*. New York: Wiley, 1985.
- [5] "Corrosion Core Concepts", *Nace.org*, 2016. [Online]. Available: <https://www.nace.org/Corrosion-101>.
- [6] P. E. Francis, "Cathodic Protection," [Online]. Available: http://www.npl.co.uk/upload/pdf/cathodic_protection_in_practise.pdf.
- [7] V. Ashworth, "Principles of Cathodic Protection", *Elsevier B.V.*, vol. 2, no. 3, pp. 10.3-10.28, 2010.
- [8] A. Tiwari, L. Hihara and J. Rawlins, *Intelligent coatings for corrosion control*. Butterworth-Heinemann, 2014, pp. 1-15.
- [9] J. Ault, "The Use of Coatings for Corrosion Control on Offshore Oil Structures", *Journal of Protective Coatings and Linings*, vol. 23, no. 4, pp. 42-47, 2006.
- [10] *Recommended Practice DNV-RP-B401 - Cathodic Protection Design*, 2nd ed. Det Norske Veritas, 2011.
- [11] D. Baxter and J. Britton, "OFFSHORE CATHODIC PROTECTION 101 WHAT IS IT AND HOW DOES IT WORK?", *Deepwater*, 2013. [Online]. Available: <http://www.cathodicprotection101.com/>.
- [12] W. Hartt and E. Lemieux, "A Principal Determinant in Cathodic Protection Design of Offshore Structures—The Mean Current Density", *Corrosion*, vol. 56, no. 10, pp. 988-997, 2000.

Appendix A – DNV-RP-B401 Tables & Figures [10]

Table A-1: Recommended initial and final design current densities (A/m²) for seawater exposed bare metal surfaces, as a function of depth and ‘climatic region’ based on surface water temperature.

Depth (m)	‘Tropical’ (> 20 °C)		‘Sub-Tropical’ (12- 20 °C)		‘Temperate’ (7-11 °C)		‘Arctic’ (< 7 °C)	
	initial	final	initial	final	initial	final	initial	final
0-30	0.150	0.100	0.170	0.110	0.200	0.130	0.250	0.170
>30-100	0.120	0.080	0.140	0.090	0.170	0.110	0.200	0.130
>100-300	0.140	0.090	0.160	0.110	0.190	0.140	0.220	0.170
>300	0.180	0.130	0.200	0.150	0.220	0.170	0.220	0.170

Table A-2: Recommended mean design current densities (A/m²) for seawater exposed bare metal surfaces, as a function of depth and ‘climatic region’ based on surface water temperature.

Depth (m)	‘Tropical’ (> 20 °C)	‘Sub-Tropical’ (12- 20 °C)	‘Temperate’ (7-11 °C)	‘Arctic’ (< 7 °C)
0-30	0.070	0.080	0.100	0.120
>30-100	0.060	0.070	0.080	0.100
>100-300	0.070	0.080	0.090	0.110
>300	0.090	0.100	0.110	0.110

Table A-3: Recommended mean design current densities for protection of reinforcing steel (i.e. in concrete structures) as a function of depth and ‘climatic region’ based on surface water temperature. The current densities in A/m² refer to the steel reinforcement surface area, not surface area of concrete.

Depth (m)	‘Tropical’ (> 20 °C)	‘Sub-Tropical’ (12- 20 °C)	‘Temperate’ (7-11 °C)	‘Arctic’ (< 7 °C)
0-30	0.0025	0.0015	0.0010	0.0008
>30-100	0.0020	0.0010	0.0008	0.0006
>100-300	0.0010	0.0008	0.0006	0.0006

Table A-4: Recommended constants a and b for calculation of paint coating breakdown factors.

Depth (m)	Recommended a and b values for Coating Categories I, II and III		
	I (a = 0.10)	II (a = 0.05)	III (a = 0.02)
0-30	b = 0.10	b = 0.025	b = 0.012
>30	b = 0.05	b = 0.015	b = 0.008

<i>Alloying/Impurity Element</i>	<i>Zn-base</i>	<i>Al-base</i>
Zn	Rem.	2.5-5.75
Al	0.10-0.50	Rem.
In	Na	0.015-0.040
Cd	< 0.07	< 0.002
Si	Na	< 0.12
Fe	< 0.005	< 0.09
Cu	< 0.005	< 0.003
Pb	< 0.006	Na

<i>Anode Material Type</i>	<i>Environment</i>	<i>Electrochemical Capacity (Ah/kg)</i>	<i>Closed Circuit Potential (V)</i>
Al-based	seawater	2,000	-1.05
	sediments	1,500	-0.95
Zn-based	seawater	780	-1.00
	sediments	700	-0.95

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

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.

<i>Anode Type</i>	<i>Anode Utilization Factor</i>
Long slender stand-off $L \geq 4r$	0.90
Short slender stand-off $L < 4r$	0.85
Long flush mounted $L \geq 4 \cdot \text{width}$ and $L \geq 4 \cdot \text{thickness}$	0.85
Short flush-mounted, bracelet and other types	0.80

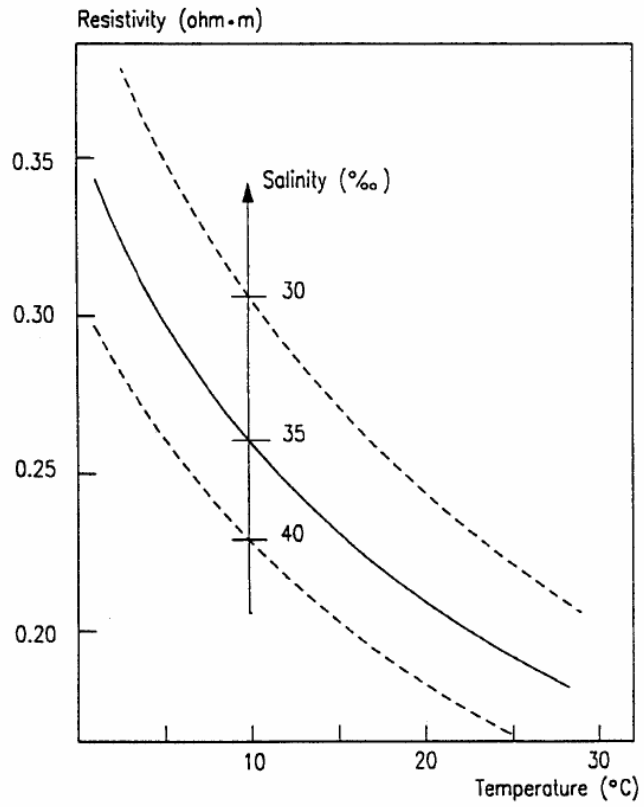


Figure A-1 – Seawater resistivity as a function of temperature.

Appendix B – Excel Spreadsheet Calculations of Cathodic Protection System of Submerged Zone

Submerged Zone		
Radius =	0.75	m
Length =	50	m
Surface Area =	239.03	m ²

Initial Current Density =	0.12	A/m ²	Table A-1
Final Current Density =	0.08	A/m ²	Table A-1
Mean Current Density =	0.06	A/m ²	Table A-2

Current Demand		Coating Breakdown Factor Calcs					
initial =	28.68 A	fc =	1				
final =	19.12 A	fcm =	1	a =	0.1	b =	0.05
mean =	8.61 A	fcf =	0.6	a =	0.1	b =	0.05

Anode Calculations		
Design Life =	20	years
Anode Type =	Al-based	
Electrochemical Capacity =	2000	Ah/kg
Utilization factor =	0.9	
Design Potential =	-0.95	V
Anode Potential =	-1.05	V
Resistance (i) =	0.065	ohm
Resistance (f) =	0.088	ohm
Current Output/Anode (i) =	1.55	A
Current Output/Anode (f) =	1.13	A
Anode Mass Required =	838	kg
Current Capacity/Anode (i) =	30.41	
Current Capacity/Anode (f) =	3.04	

Resistance Formula Calculations			
initial	p =	22	ohm-cm
	L =	160	cm
	c =	77.30	cm
	r =	12.31	cm
	R =	0.065	ohm
	mass =	148	kg
final	p =	22	ohm-cm
	L =	144	cm
	c =	77.30	cm ²
	r =	5.66	cm
	R =	0.088	ohm
	mass =	14.8	kg

Number of Anodes Required	
initial =	19 nodes
final =	13 nodes
mean =	6 nodes
Controlling # =	19 nodes
Anode Mass Check =	2812 kg

Criteria Check	Anode	Design
mean capacity	577.81	172.10
initial current demand	29.40	28.68
final current demand	21.56	19.12