Cathodic Protection Of Stainless And Galvanised Steels In Marine Environments Using Aluminium And Zinc As Sacrificial Anodes

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Abstract—**Cathodic protection is a corrosion control method that gives optimum protection against corrosion for Stainless and Galvanised Steel in marine environments. This project presents the results of a study on the effectiveness of cathodic protection in marine environments. Experimental tests were carried out to characterize the stainless steel and galvanized steel samples using a Scanning Electron Microscope (SEM) before and after introducing the samples into a marine environment, so also the chemical composition of the marine was duly observed as marine water was in different locations. The result demonstrated for both galvanized and stainless steel shows that there was weight loss in both samples after being immersed in marine water for 2 months which galvanised steel sample lost 0.029kg of its 0.121kg initial weight and the stainless steel lost 0.005kg of its 0.362kg initial weight where we concluded that stainless steel sample lost lesser weight due to its high resistivity to corrosion. A good agreement was observed for corrosion rate between the two samples where the galvanized steel corroded 1.5mm/yr of its total surface area and stainless steel corroded only 0.3mm/yr of its total surface area.**

I. INTRODUCTION

Corrosion can be defined as the destruction or deterioration of the material because of the reaction with the environment. Most of the materials that undergo corrosion are metal, so some insist definition of the corrosion should be specific to the metal. In 1987, Fontana suggested that all materials including ceramic, polymer and other non-metallic materials which contribute to the corrosion reaction should be taken into consideration[1].

Corrosion weakens the strength and causes failure in the material. Protecting a material from undergoing corrosion becomes crucial, especially in marine environments. Protection needs to be done on the material to reduce the corrosion rate in other to minimize materials and money being wasted[1].

Metallic equipment, vessels and structures in marine environments are always subject to corrosion, which seriously affects their lifespan, efficiency, sensitivity and quality if not correctly monitored and avoided. The annual cost of marine corrosion has increased until it is estimated today at 4 % of the Gross National Product. Many different types of destructive attacks can occur to structures, ships and other equipment used in seawater service. The term 'aqueous corrosion' describes the majority of the most troublesome problems encountered in contact with seawater, but atmospheric corrosion of metals exposed on or near coastlines, and hot salt corrosion in engines operating at sea or taking in salt-laden air are equally problematical and like aqueous corrosion require a systematic approach to eliminate or manage them *(Jin-Seok & Jong-Do, 2004).*

Ordinarily, air can have some amount of corrosive elements like gases, inert and aggressive dust, soot, and humidity (in the form of fog, dew, rain, and snow). The quantity of these elements may vary, depending on location and time of the year. Corrosion of materials in an environment with air containing sulphur oxides is always greater than the same materials in an environment with clean air. Fair enough, the amount of Sulphur dioxide in the atmosphere has reportedly decreased drastically during recent years[5].

On the other hand, the corrosion conditions in soil are very complicated and variations can be great between different locations; even those close to each other. Soil can contain weathered products, free or bound salts, acids and alkalis, mixtures of organic substances, oxidizing or reducing fungi, microorganisms etc. Depending on its structure, soil has different degrees of permeability to air and moisture. Normally, the oxygen content is less than in the air, while the carbon dioxide content is higher[5].

1. What is Cathodic Protection?

Cathodic protection is a corrosion control method by which electrons are supplied to the metal structure to be protected. For example, the corrosion of a steel structure in an acid environment involves the following electrochemical equation:

$$Fe \longrightarrow Fe^{2+} + 2e^{-}$$
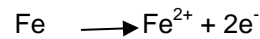
If electrons are supplied to the steel structure, metal dissolution (corrosion) will be suppressed and the rate of hydrogen evolution will increase. Thus if electrons are continually supplied to the steel structure, corrosion will be suppressed. Electrons for cathodic protection can be supplied by:

(1) An external DC power supply,
(2) Galvanic coupling with a more anodic metal than the one being protected.

All cathodic protection systems require an anode, a cathode, an electric circuit between the anode and cathode, and an electrolyte. The anode is the electrode at which a net oxidation reaction occurs, whereas cathodes are electrodes at which net reduction reactions occur. Thus, cathodic protection will not work on structures exposed to air environments. The air is a poor electrolyte, and it prevents current from flowing from the anode to the cathode.

2. Cathodic Protection can be accomplished by two widely used methods:

i. By coupling a given structure (say Fe) with a more active metal such as zinc or magnesium. This produces a galvanic cell in which the active metal works as an anode and provides a flux of electrons to the structure, which then becomes the cathode. The cathode is protected and the anode progressively gets destroyed, and is hence, called a sacrificial anode.

ii.   The second method involves impressing a direct current between an inert anode and the structure to be protected. Since electrons flow to the structure, it is protected from becoming the source of electrons (anode). In impressed current systems, the anode is buried and a low-voltage DC is impressed between the anode and the cathode.

This study aims to protect Stainless And Galvanised Steel from corrosion in marine environments using the Cathode Protection System where Magnesium and Zinc are used as sacrificial anodes.

The findings of this study are important in other to understand the theory of the Cathodic Protection System. A comparison of results and real application for the Cathodic Protection System can be done to further understand the effect of the parameters upon the Cathodic Protection System.

Specific Objectives

- To investigate the weight loss of the samples
- To determine the corrosion rate of the samples
- To characterize the samples before and after inversion by Scanning Electron Microscope (SEM)
- To analyse the chemical compositions of the marine samples

Limitations

1. Design a cathodic protection system for stainless and galvanized steel immersed in a marine environment by considering the current required, selecting the anode materials which are Magnesium and Zinc, circuit resistance and power source selection.

2. Determine the effectiveness of both sacrificial anode systems on corrosion behaviour on stainless and galvanized steel by measuring the potential for steels in marine environments.

II.   General Review

The effect of the galvanic couples between metals has certainly been observed for a long time (maybe by the Romans). In Florence, in 1792, Giovanni Fabbroni was the first one to describe bi-metallic corrosion [2].

In 1802 Alessandro Volta described the principles of the effect of a continuous electric current on the oxidation of metals: "The oxidation strongly increases on the metal from which the current goes out to go in water or other oxidant liquids. The oxidation decreases or is eliminated on the metal in which the current goes in and on which hydrogen is released " [2].

The first application of cathodic protection by a "galvanic system" using "sacrificial anodes" was done in seawater, an ideal environment, for the implementation of this technique because of its high conductivity and strong homogeneity. In 1806, Sir Humphrey Davy advanced the idea of a favourable effect on the corrosion of copper in seawater in contact with zinc, tin or iron. Following an order from the Royal Navy in 1824, he established within two years the basic principles of cathodic protection in seawater. He attached four cast iron anodes, two to the stern and two to the bow, with a surface ratio of 1:80 of the surface of copper, on the SS Samarang, a wooden warship with a copper hull which showed signs of corrosion after being used for three years[2].

The installation of iron plates to protect the copper sheath of boats with wooden hulls of the British Royal Navy was thus introduced. Thereafter, zinc replaced iron, ensuring the galvanic protection of steel. The real efficiency of this system was certainly low

because of the level of purity of the used zinc at this time[2].

The law established by Faraday in 1829 to quantify electrolysis was a major progress in the explanation and the design of galvanic systems[2].

In 1865, Antoine Becquerel, studying the protection of boats with zinc, writes: "Another use could be done with some chance of success: It is about the protection of cast iron piping buried in wet grounds "[2].

The first application of cathodic protection by the impressed current was introduced to fight against galvanic corrosion in the condensers of boilers used for steam machines at the end of the 19th century. This system used some soft iron for the anodes and the current was provided by low voltage dynamos generating a 6 to 10 V direct current. This process, called the "Cumberland Electrolytic System", was introduced by Elliott Cumberland in Great Britain, the zinc galvanic anodes used then quickly became inefficient because of the deposits forming and it required frequent changes. This technique was applied for the protection of steam machines, particularly on railway engines. It was used by the British Army during the First World War and on boats[3].

The first use of cathodic protection for buried water, gas or petroleum products pipelines took place in the 1920s in the USA, with the use of windmills before the appearance of rectifiers. In the 1930s, Illinois Bell Telephone Co. protected lead-sheathed cables with CuO_2 rectifiers [3].

In Western Europe, cathodic protection has been developed in addition to the "polarized drainage" of the stray currents set up against the fast attacks by corrosion of the ground pipes pulled along by the electrification of the networks with direct current. The regulation sometimes slowed down the implementation of these techniques, particularly in France[3].

In Belgium, Distrigaz studied this method (called " électroprotection") since 1930 and tried it out since 1934, mainly against "electrolytic" corrosion by stray currents, in addition to the polarized drainages. Cathodic protection by the impressed current was introduced in France only in 1946 by the RAP for its South-west network (with the help of Distrigaz). At the same time, Gaz de France set up electrochemical prediction methods at the instigation of J Maurin. At the same time, magnesium anodes were installed on part of the piping between Gennevilliers and Saint-Ouen[3].

Offshore, cathodic protection by galvanic anodes was initially used in Lake Maracaibo (Venezuela). An application of the protection by the impressed current on an underwater pipeline conveying water between Miami and Keywest was noticed in 1935. A broad application of cathodic protection was developed on the platforms in the Gulf of Mexico at the end of the Forties, by the use of suspended magnesium anodes, frequently replaced[3].

The real industrial applications of cathodic protection were linked to the development of techniques during the Second World War: for example the first rectifiers with semiconductors and magnesium anodes[4].

The criterion is -0.85 V / sat. Cu-CuSO4 set up by R. J. Kuhn in 1933 for the buried pipelines was theoretically interpreted at the same time by T.P. Hoar in 1937 and R.B. Mears and R.H. Brown in 1938. W J Schwerdtfeger confirmed this criterion thanks to tests on the grounds in 1951 and seawater in 1958[4].

In 1952, Marcel Pourbaix and the Comité Technique Belgesur la protection cathodique (CT4) wrote: "Since 1933 cathodic protection installations of steel pipes buried in the ground were developed (mainly

for the distribution of water, gas and oil). These installations are now perfectly efficient and can be easily controlled, thanks, in particular, to a better knowledge of the scientific bases of the electrochemical behaviour of iron and ordinary steel. Cathodic protection is destined for a great future in many other cases, and further scientific and technical studies about this subject are required..."[6].

To understand cathodic protection, you must first understand how corrosion is caused. For corrosion to occur, three things must be present:

1. Two dissimilar metals
2. An electrolyte (water with any type of salt or salts dissolved in it)
3. A metal (conducting) path between the dissimilar metals

The two dissimilar metals may be different alloys such as steel and aluminum but are more likely to be microscopic or macroscopic metallurgical differences on the surface of a single piece of steel. In this case, we will consider freely corroding steel, which is non-uniform.

If the above conditions exist, the following reaction takes place at the more active sites: (two iron ions plus four free electrons).

$$2Fe => 2Fe^+ + 4e^-$$

The free electrons travel through the metal path to the less active sites, where the following reaction takes place: (oxygen gas is converted to oxygen ion - by combining with the four free electrons - which combines with water to form hydroxyl ions).

$$O_2 + 4e^- + 2H_2O => 4\ OH^-$$
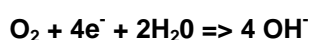
Recombinations of these ions at the active surface produce the following reaction, which yields the iron-corrosion product ferrous hydroxide: (iron combining with oxygen and water to form ferrous hydroxide).

$$2Fe + O_2 + 2H_2O => 2Fe\ (OH)_2$$
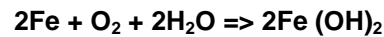
This reaction is more commonly described as 'current flow through the water from the anode (more active site) to the cathode (less active site).'

2.1 How does cathodic protection stop corrosion?

Cathodic protection prevents corrosion by converting all of the anodic (active) sites on the metal surface to cathodic (passive) sites by supplying electrical current (or free electrons) from an alternate source.

Usually, this takes the form of galvanic anodes, which are more active than steel. This practice is also referred to as a sacrificial system since the galvanic anodes sacrifice themselves to protect the structural steel or pipeline from corrosion.

In the case of aluminium, the reaction at the aluminium surface is: (four aluminium ions plus twelve free electrons)

$$4Al => 4AL^{+++} + 12\ e^-$$

and at the steel surface: (oxygen gas converted to oxygen ions which combine with water to form hydroxyl ions).

$$3O_2 + 12e^- + 6H_2O => 12OH^-$$

As long as the current (free electrons) arrives at the cathode (steel) faster than oxygen arrives, no corrosion will occur[7].

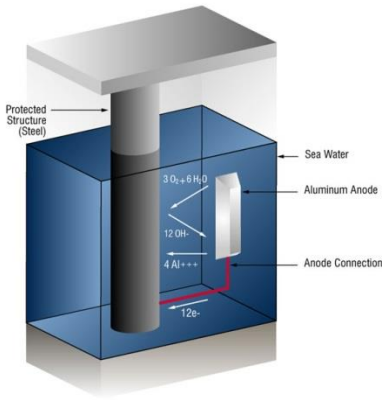Cathodic Protection can be accomplished by two widely used methods:

Figure 1: Sacrificial anode system in seawater [8}

> *By coupling a given structure (say Fe) with a more active metal such as zinc or magnesium. This produces a galvanic cell in which the active metal works as an anode and provides a flux of electrons to the structure, which then becomes the cathode. The cathode is protected and the anode progressively gets destroyed, and is hence, called a sacrificial anode.*

2.2 Basic considerations when designing sacrificial anode systems

The electrical current an anode discharges is controlled by Ohm's law, which is:

I=E/R

I= Current flow in amps

E= difference in potential between the anode and cathode in volts

R= Total circuit resistance in ohms

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

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

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

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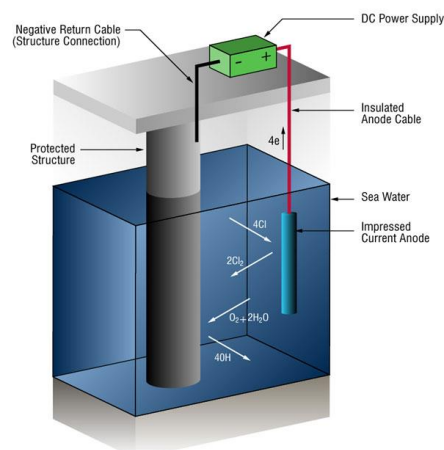

Figure 2: Impressed-current cathodic-protection system in seawater [8]

> *The second method involves impressing a direct current between an inert anode and the structure to be protected. Since electrons flow to the structure, it is protected from becoming the source of electrons (anode). In*

impressed current systems, the anode is buried and a low-voltage DC is impressed between the anode and the cathode.

2.3 How do we know when we have enough cathodic protection?

We can verify that there's enough current by measuring the potential of the steel against a standard reference electrode, usually silver /chloride (Ag/AgCl sw.), but sometimes zinc (sw.).

Current flow onto any metal will shift its normal potential in the negative direction. History has shown that if steel receives enough current to shift the potential to (-) 0.800 V vs. silver/silver chloride (Ag / AgCl), the corrosion is essentially stopped.

Due to the nature of the films which form, the minimum (-0.800 V) potential is rarely optimum, so designers try to achieve a potential between (-) 0.950 V and (-) 1.000 V vs. Ag/AgCl sw.
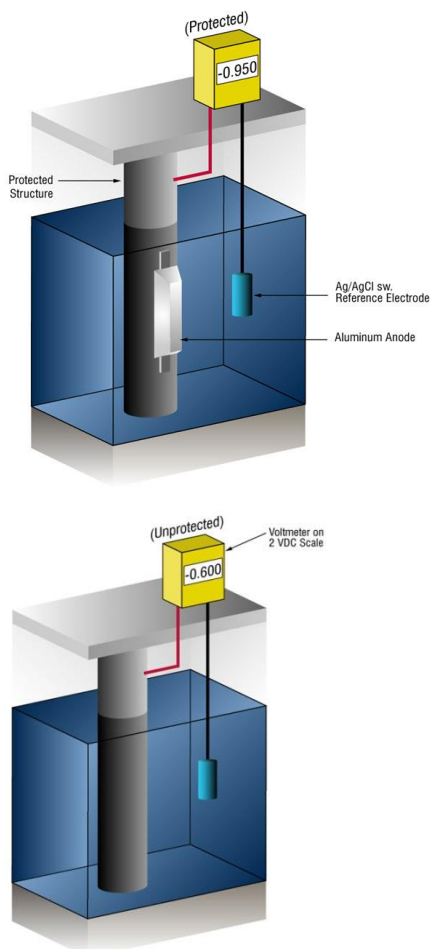

Fig 3: Impressed-current cathodic protection system of protected and unprotected structure in seawater [8]

III. METHODOLOGY

This chapter introduces the experimental procedures for the Cathodic Protection Of Stainless And Galvanised Steelin Marine environments Magnesium And Zinc As Sacrificial Anodes that shall be carried out in the field and approved by the principals to make Cathodic Protected Stainless And Galvanised Steel Where Magnesium And Zinc Are Used As Sacrificial Anodes.

3.1 Materials
- Zinc
- Magnesium
- Galvanised Steels
- Stainless Steels
- Marine H_2O
- Beakers

3.2 Equipments
- pH Meter
- Scanning Electron Microscope (SEM)
- Voltmeter

3.3 Sample Preparation
- The samples to be protected are introduced into the galvanic protection design setup.
- The sacrificial anode is then connected to the sample to be protected.
- The electrolyte (marine H_2O) is then introduced into the setup.
- The ammeter is connected to the setup.
- The anodic protection procedure is commenced.

Figure 4 shows the samples and the materials used to carry out the practical work of this project.

Fig 4: Stainless Steel Sample

Fig 7: Ammeter

Fig 5: Galvanised Steel Sample

Fig 8: Copper Wire

Fig 6: pH Meter

Fig 9: SEM

Fig 10: Zinc Sacrificial Anode

3.3.1 Laboratory Work and Experiment

- The acidity or alkalinity of the marine water is considered.

- The samples are taken to the Scanning Electron Microscope (SEM) to know the state of the samples before and after they undergo corrosion.

3.4 Cathodic Protection Design

Required information.

Before deciding which type, of galvanic cathodic protection system will be used and before the system is designed, certain preliminary data must be gathered.

3.4.1 Physical Dimensions Of Structure To Be Protected

One important element in designing a cathodic protection system is the structure's physical dimensions (for example, length, width, height, and diameter). These data are used to calculate the surface area to be protected.

3.4.2 Drawing Of Structure To Be Protected

The installation drawings must include sizes, shapes, material types, and locations of parts of the structure to be protected.

3.4.2 Electrical Isolation

If a structure is to be protected by the cathodic system, it must be electrically connected to the anode. Sometimes parts of a structure or system are electrically isolated from each other by insulators. For example, in a gas pipeline distribution system, the inlet pipe to each building might contain an electric insulator to isolate in-house piping from the pipeline. Also, an electrical insulator might be used at a valve along the pipeline to electrically isolate one section of the system from another. Since each electrically isolated part of a structure would need its cathodic protection, the locations of these insulators must be determined.

3.4.3 Corrosion History Of Structures In The Area

Studying the corrosion history in the area can prove very helpful when designing a cathodic protection system. The study should reinforce predictions for the corrosivity of a given structure and its environment; in addition, it may reveal abnormal conditions not otherwise suspected. Facilities personnel can be a good source of information for corrosion history.

3.4.4 Electrolyte pH Survey

Corrosion is also proportional to electrolyte pH. In general, steel's corrosion rate increases as pH decreases when soil resistivity remains constant.

3.4.5 Current Requirement

A critical part of design calculations for cathodic protection systems on existing structures is the amount of current required per square foot (called current density) to change the structure's potential to -0.85 volts. The current density required to shift the potential indicates the structure's surface condition. A well-coated structure (for example, a pipeline well coated with coal-tar epoxy) will require a very low

current density (about 0.05 milliampere per square foot); an uncoated structure would require high current density (about 10 milliamperes per square foot). The average current density required for cathodic protection is 2 milliamperes per square foot of bare area.

The amount of current required for complete cathodic protection can be determined in three

ways:

- An actual test on existing structures using a temporary cathodic protection setup.

- A theoretical calculation based on coating efficiency.

- An estimate of current requirements using tables based on field experience.

3.5 Weight Loss

The weight of all samples or structures to be protected should be considered before subjecting them to a corrosive environment, that is, measuring the weight of the structure before and after it undergoes corrosion. So also the weight of the sacrificial anodes should be taken both before and after undergoing corrosion in the marine water.

Calculating the total weight loss (W) is indicated in equation 1.1:

$$W = W_i - W_f$$

Where **W** represents total weight loss, W_i represents initial weight and W_f represents final weight.

3.6 Corrosion Rate

Certain preliminaries have to be taken into consideration while calculating the corrosion rate of the protected structure, these preliminaries are the total weight loss, the density, the area to be protected and the time

the structure or sample was put into the marine water.

Calculating the corrosion rate (CR) is indicated in equation 1.2:

$$CR = (87.6) \frac{W}{Density \times Area \times Time}$$

Where **CR** represents the Corrosion Rate, and **W** is the Weight Loss.

3.7 Determining Type And Design Of Cathodic Protection System

When all preliminary data have been gathered and the protective current has been estimated, the design sequence can begin. The first question to ask is: which type (galvanic or impressed current) cathodic protection system is needed? Conditions at the site sometimes dictate the choice. However, when this is not clear, the criterion used most widely is based on the current density required and soil resistivity. If the soil resistivity is low (less than 5000 ohm-centimetres) and the current density requirement is low (less than 1 milliampere per square foot), a galvanic system can be used. However, if the soil resistivity and/or current density requirement exceed the above values, an impressed current system should be used.

3.8 Sacrificial Anode (Galvanic) Cathodic Protection System Design

The following nine steps are required when designing galvanic cathodic protection systems.

3.8.1 Review soil resistivity: The site of lowest resistivity will likely be used for anode location to minimize anode-to-electrolyte resistivity. In addition, if resistivity variations are not significant, the average resistivity will be used for design calculations.

3.8.2 Select anode: Galvanic anodes are usually either magnesium or zinc. Zinc anodes are used in extremely corrosive soil (resistivity below 2000 ohm centimetres). Data from commercially available anodes must be reviewed. Each anode specification will include anode weight, anode dimensions, and package dimensions (anode plus backfill).

3.8.3 Calculate net driving potential for anodes: The open-circuit potential of standard alloy magnesium anodes is approximately -1.55 volts to a copper copper sulfate half-cell. The open-circuit potential of high-manganese magnesium anodes is approximately - 1.75 volts to a copper-copper sulfate half-cell.

a) The potential of iron in contact with soil or water usually ranges around -0.55 volts relative to copper-copper sulfate. When cathodic protection is applied using magnesium anodes, the iron potential assumes some value between -0.55 and - 1.0 volt, depending on the degree of protection provided. In highly corrosive soils or waters, the natural potential of iron may be as high as -0.82 volts relative to copper copper sulfate. From this, it is evident that -0.55 volts should not be used to calculate the net driving potential available from magnesium anodes.

b) A more practical approach is to consider iron polarized to -0.85 volt. On this basis, standard alloy magnesium anodes have a driving potential of 0.70 volts (1.55-0.85 0.70) and high-potential magnesium anodes have a driving potential of 0.90 volts (1.75-0.85 0.90). For cathodic protection design that involves magnesium anodes, these potentials, 0.70 and 0.90 volts, should be used, depending on the alloy selected.

3.8.4 Calculate the number of anodes needed to meet grounded resistance limitations: The total resistance (RT) of the galvanic circuit is given by Equation 2-2:

RT = RA + RW +RC (eq 2-2)

where RA is the anode-to-electrolyte resistance, RW is the anode lead wire resistance, and RC is the structure-to-electrolyte resistance. The total resistance also can be found by using Equation 2-3:

RT = ΔE/I (eq 2-3)

where E is the anode's driving potential required to achieve cathodic protection. RC Equation 2-2 can be calculated by using Equation 2-4:

RC = R x A (eq 2-4)

where R is the average coating resistance, in ohms per square feet, at the end of the proposed lifetime for the system (R is specified by the supplier), and A is the structure's surface area in square feet. Assuming RW in Equation 2-2 is negligible, that anode-to-electrolyte resistance can then be calculated from Equation 2-5:

Ra = RT – RC (eq 2-5)

Which gives the maximum allowable groundbed resistance; this will dictate the minimum number of anodes required (as the number of anodes decreases, groundbed resistance increases). To calculate the number of anodes required, Equation 2-6 is used:

N = ((0.0052)/(Ra)(L)) x [ln 8L/d] (eq 2-6)

where N is the number of anodes, ρ is the soil resistivity in ohms, Ra is the maximum allowable grounded resistance in ohms (as computed in Equation 2-5), L is the length of the backfill column in feet (specified by the supplier) and d is the diameter of the backfill column in feet (specified by the supplier).

3.8.5 Calculate the number of anodes for the system's life expectancy: Each cathodic protection system will be designed to protect a structure for a given number of years. To meet this lifetime

requirement, the number of anodes (N) must be calculated using Equation 2-7:

Chemical composition of Stainless Steel						
C	Si	Mn	P	S	Ni	Cr
Max 0.15	Max 1.00	Max 2.00	Max 0.045	Max 0.030	6.00-8.00	16.00-18.00

$$N = ((L)(I)/(49.3)(W)) \text{ (eq 2-7)}$$

Where L is the expected lifetime in years, W is the weight (in pounds) of one anode, and I is the current density required to protect the structure (in milliamperes).

3.8.6 Select the number of anodes to be used: The greater value of Equation 2-6 or Equation 2-7 will be used as the number of anodes needed for the system.

3.8.7 Select groundbed layout: When the required number of anodes has been calculated, the area to be protected by each anode is calculated by Equation 2-8:

$$A = AT/N \text{ (eq 2-8)}$$

Where A is the area to be protected by one anode, AT is the total surface area to be protected, and N is the total number of anodes to be used. For galvanic cathodic protection systems, the anodes should be spaced equally along the structure to be protected.

3.8.8 Calculate life-cycle cost for proposed design: NACE Standard RP-02 should be used to calculate the system's life-cycle cost. The design process should be done for several different anode choices to find the one with minimal life-cycle cost.

3.8.9 Prepare plans and specifications: When the design procedure has been done for several different anodes and the final anode has been chosen, plans and specifications can be completed. (Introduction to Electrical Design for Cathodic Protection Systems et all).

IV. RESULTS AND DISCUSSION

Chemical Composition of Materials Used

4.1 Stainless Steel

Table 1. Chemical composition of stainless steel

4.2 Galvanised Steel

The table below shows the chemical composition of the Galvanised Steel material used to carry out the galvanic cathodic protection as required in this project. It is showing the actual amount of other alloyed materials in percentage present in the Galvanised Steel.

Table 2. Chemical composition of galvanised steel

Chemical Composition of Galvanised Steel			
C	Si	Mn	P
Max 0.25	0.05-0.11	Max 1.3	Max 0.05

4.3 Aluminium Sacrificial Anode

The table below shows the chemical composition of the Aluminium sacrificial anode used to carry out the galvanic cathodic protection on both stainless steel and galvanized steel as required in this project. The Beralin Alloy was used as it is more suitable for carrying out the test in other to achieve the accurate test result.

Table 3. Chemical composition of aluminium sacrificial anode

	Beralin Alloy	Bacalin Alloy
Zn	3.5 – 6.5%	3.5 – 6.5%
Mn	0.01% max	0.01 – 0.25%
Fe	0.13% max	0.22% max
Si	0.10% max	0.10% max
Cu	0.006% max	0.01% max
Al	Remainder	Remainder

4.1.4 Zinc sacrificial Anode

Table 4. Chemical composition of zinc sacrificial anode

Chemical Composition of Zinc Anode	
Al	0.10 – 0.50%
Cd	0.025 – 0.07%
Fe	0.005% Max
Pb	0.006% Max
Cu	0.005% Max
Others	0.10% Max
Zn	Remainder

Table 5 shows the chemical composition of the Zinc anode used to carry out the galvanic cathodic protection on both stainless steel and galvanized steel as required in this project. It is shown that the Zinc anode used is suitable for use in carrying out the tests needed in this project.

4.1.5 Chemical Analysis of the Sea Water

In Table 5 below, the pH of Badagry, Ikorodu and Oniru media were 7.07, 8.32 and 6.66 respectively. It is shown that the salinity of Badagry, Ikorodu and Oniru are 0.256mg/l, 1.286mg/l and 0.559mg/l

respectively. The following elements were also present in the media in different proportions: Chloride, Sodium, Calcium and Magnesium.

Table 5. Chemical composition of seawater from different locations

Medium/Parameters	Badagry	Ikorodu	Oniru
pH Value	7.07	8.32	6.66
Conductivity ($\mu s/cm$)	515.6	7.04	962
Salinity (mg/l)	0.256	1.286	0.559
Temperature (^{o}C)	24.5	25	24.9
TDS (mg/l)	208.7	35607.00	385.7
Acidity	80	85	83
Alkalinity	100	500	508
Chloride	50.61mg/l	812.624	817.624
Sodium	10.06	11.102	9.08
Calcium	2.06	65.412	60.251
Magnesium	2.996	2150.0	203.0

4.1.6 Scanning Electron Microscope Results

Figures 11 and 12 below are the results of the electron scanning tests carried out on the Zinc samples using a Scanning electron Microscope (SEM) machine. The images are tagged according to the description of each sample that is, the samples of the Zinc when immersed in the media and when it's not immersed in the media.
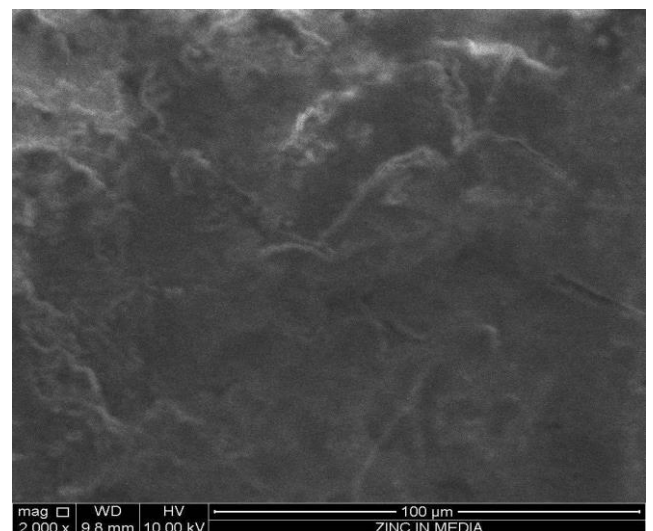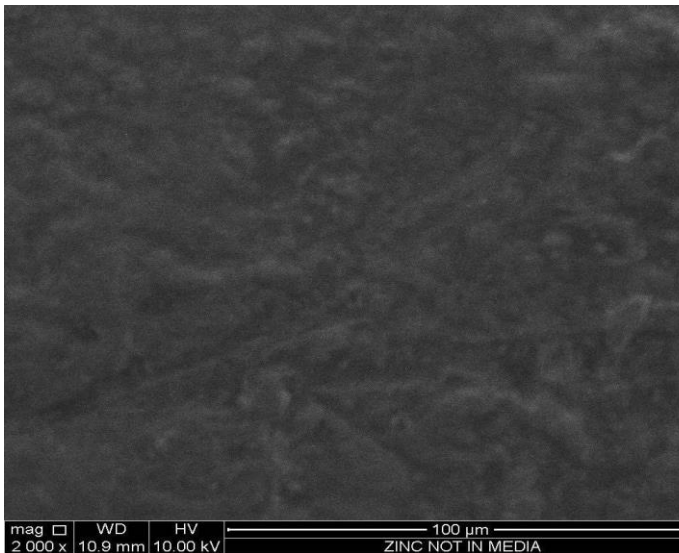

Fig 11: Zinc anode in Media

Fig 12: Zinc anode not in media

Function of the Equipment Used

a. Scanning Electron Microscope (SEM)

A scanning electron microscope which is also known as SEM scans a focused electron beam over the surface of a sample to create an image. The electrons in the beam interact with the sample, producing various signals that can be used to obtain information about the surface topography and composition of the sample.

b. pH Meter

It is an electric device that is used to measure hydrogen-ion activity in a solution. In other words, it is used to measure the level of acidity or alkalinity in a solution. Fundamentally, a pH meter consists of a voltmeter attached to a pH-responsive electrode and a reference (unvarying) electrode.

c. Ammeter

The ammeter is an instrument used for measuring current in units of amperes. It must be connected in series with the path of the current being measured. If the ammeter is set up in parallel, it will create a short circuit and will not measure the current correctly.

Calculation for Weight Loss

The formula for weight loss $(W) = W_i - W_f$

where W = Total Weight Loss

W_i= Initial Weight

W_f= Final Weight

Calculating the Weight Loss of Galvanised Steel (W_{GS})

The formula for weight loss $(W) = W_i - W_f$

where W = Total Weight Loss

W_i= Initial Weight

W_f= Final Weight

$W_i = 0.121$kg, $W_f = 0.092$kg

$0.121 - 0.092 = 0.029$kg

Therefore the Total Weight Loss (W_{GS}) for Galvanised Steel is 0.029kg

Calculating the Weight Loss of Stainless Steel (W_{SS})

$W_i = 0.362$kg, $W_f = 0.301$kg

$0.362 - 0.357 = 0.005$kg

Therefore the Total Weight Loss (W_{SS}) for Stainless Steel is 0.005kg

Calculating for Corrosion Rate

The formula for Corrosion Rate $CR = \dfrac{(87.6)}{W}$

Density x Area x Time

Where **CR** represents the Corrosion Rate, and **W** is the Weight Loss.

Corrosion Rate for Galvanised Steel

CR= (87.6) W_{GS}

where W_{GS} = 0.029kg (29000mg)

Density x Area x Time

Density of GS = 7.85g/cm^3

Time = 1,440hrs (2 months)

Area = Length x Breath   where Length = 30cm

Breath = 5cm

Area = 30 x 5 = 150cm^2

CR = (87.6)   29000

7.85 x 150 x 1440

CR = 87.6 x 0.01710309

Therefore the Corrosion Rate (CR$_{GS}$) for Galvanised Steel is 1.5mm/yr

Corrosion Rate for Stainless Steel

Weight Loss of Stainless Steel (W_{SS}) is 0.005kg (5000mg)

The density of Stainless Steel is 7.75g/cm^3

The area of Stainless Steel is 150cm^2

The time of exposure of the Stainless Steel is 1,440hrs (2 months)

CR = (87.6)   5000

7.75 x 150 x 1440

CR = 87.6 x 0.00298686

The Corrosion Rate for Stainless Steel (CR$_{SS}$) = 0.3mm/yr

4.2   Result Analysis for Galvanised and Stainless Steels

Table 6. Total result on galvanized steel and stainless steel

Materials/Results	Galvanised Steel	Stainless Steel
Total Weight Loss (W)	0.029kg	0.005kg
Corrosion Rate (CR)	1.5mm/yr	0.3mm/yr

Table 6 shows that Stainless Steel is more corrosive resistant than Galvanised Steel as they were both subjected to the same media and protected by the same sacrificial anodes over the same period.

The use of sacrificial anodes in protecting a metal or steel structure because the sacrificial anodes used are highly active metals that are used to prevent a less active material surface from corroding. This sacrificial anode is created from a metal alloy with a more negative electrochemical potential than the other metal it will be used to protect. The sacrificial anode will be consumed in place of the metal it is protecting.

When metals come in contact with electrolytes (sea water), they undergo an electrochemical reaction known as corrosion. The whole idea of this cathodic protection is to ensure that metals last as long as they can. According to the table of Standard Reduction Potentials, the standard reduction potential of steel is about -0.76 volts.

Fig 13: Sacrificial Anodes attached to a ship

Figure 13 shows how sacrificial anodes are attached to ships used on seawater where the anodes are used to protect the body of the ship from corroding over some time and then the sacrificial anodes are replaced depending on how corroded they Each sacrificial anode has its square meter it can protect over some time before it corrodes or deteriorates totally and then replaced. The use of ships on seawater is very important and ships sail on salt water in harsh corrosive conditions for a very long time and all thanks to Cathodic Protection for making those ships survive for very long periods on open seas all across the continents in this world.

Fig 14: A deteriorating sacrificial anode

Figure 14 shows a partially corroded sacrificial anode on the hull of a ship. Since the sacrificial anode works by introducing another metal surface with a more negative electronegative and much more anodic surface. The current will flow from the newly introduced anode and the protected metal becomes cathodic creating a galvanic cell. The oxidation reactions are transferred from the metal surface to the galvanic anode and will be sacrificed in favour of the protected metal or steel structure as shown in Fig 14 above.

V.   CONCLUSION AND RECOMMENDATIONS

5.1   Conclusions

The result obtained from the practical work had successfully fulfilled the objectives of the project. The conclusions derived from this project are listed as follows:

1. The Galvanic Cathodic Protection System gives the optimum protection for both Galvanised Steel and Stainless Steel from corroding for a longer period compared to when they are not protected in marine environments.

2. Using a Galvanic Cathodic Protection System on both Galvanised steel and

Stainless Steel, we can conclude that Stainless Steel should be used to make steel structures in deep marine water as it can stay longer in marine environments without corroding compared to Galvanised Steel.

3. Results from the immersion test indicate that galvanized Steel immersed in marine water exhibits a higher corrosion rate (1.5mm/yr) and Stainless Steel immersed in marine water exhibits a lower corrosion rate (0.3mm/yr).

4. The Galvanised Steel lost more weight over 2 months and Stainless Steel lost less weight over the same period of 2 months.

5.2 Recommendations

From the study that has been successfully carried out, the following are some Recommendations that may be considered for future work:

1. Applying Galvanic Cathodic Protection on various shapes of steel in different environments and at different temperatures with other types of anodes.

2. Further studies should be made to evaluate the effect of the lifetime of the anodes on the economy of the whole process.

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