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# Determination of Number of Anodes and Groundbed Layout of Sacrificial Anodes Using a Customized Anode Sizing Software

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***ABSTRACT**: This dissertation centers on building a software that has the potency of being used for sizing anodes (Sacrificial anodes) to get the most reliable choice of the number of anodes used for the 'Galvanic Cathodic Protection' of 'subsea structures'. The environment that is under consideration in this work is the Agbami field ranging from wells 1-5, located Latitude 3.4613780 and Longitude 5.5779800 (Design Basis, AGB-CVX-GN-DSG-GN-0001-00-11) off the coast of Niger Delta and has water depth of 1,463m. The water condition is categorized to be Seawater. The potential (net initial) referencing is to Cu/CuSO4 and is taken to be 0.85 volts as given by DNV RP and BS EN 13176:2001. To effectively make use of 'sacrificial anode', the environment must be such that resistivity is not too high and flow line is bare. There is a direct proportionality between resistivity and' corrosion rate' from NACE RP 0492-92 and NACE RP 0387-87. The geometry of the anode in terms of dimensions, have corresponding weight equivalents that was inputted as part of 'structure' data in the software as anode weight. The 'structure' is designed to last for 25 years. This thesis seeks to examine one very important anode characteristic that the software outputs and is the quantity of anodes that should be used on a 'structure' and the 'ground bed layout'. The lack of balance between the quantities of anodes to suit the 'ground bed layout' can result in Hydrogen embrittlement (Hydrogen Induced Stressed Cracking), as result of oversizing. That happens when there are too many anodes for a specific area. The quantity of anodes needed and Ground Bed Layout which are 7.85 (approximately 9 anodes) and 280. 3 m2 respectively corresponds correctly to true field data as was outputted by the proprietary software.*

***KEYWORDS-** Sacrificial anode, Ground bed layout, Cathodic Protection, Sizing, Corrosivity, SQLite, Java, Umbilical, Eclipse IDE, Electronegativity.*

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## I. INTRODUCTION

'Anode sizing' for 'Cathodic Protection' (CD) remains a deterministic factor for an effective protection capability for a 'subsea structure', 'electrochemical potential' retention and guaranteeing the length of time the anode can serve when it is deployed. This informs the type, durability, effectiveness and total amount of money that could be expended for the cathodic Protection of any system (Francis, 2004). The 'sacrificial anodes' used to combat against corrosion must be appropriately and effectively sized, if it has to work properly and be fit for purpose (Francis, 2004). Besides coating of metals or steel as the first step of 'cathodic protection', 'Sacrificial Anode Cathodic Protection' as a complimentary Protection approach, remains highly applicable and indispensable if the life of steel in 'seawater' is to be guaranteed. More so, this type of protection plays an important role if the anode in question has to protect the 'structure' for the duration of time it is designed for.

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The protection of 'structures' made of steel not only concerns 'structures' in subsea but also those in mud, underground and on land. 'Sacrificial Anode cathodic protection' falls under the 'Galvanic Cathodic Protection system', which is highly dependent on the corrosion potentials of the various metals (ADGE, 2017). Based on the ambient conditions of the location of the structure, faults or inconsistencies resulting from the process of manufacture of steel and/or the reactivity level of the material used in making the 'structure' (steel), corrosion could set in (Anonymous, 1985). In a situation where there is no existent 'cathodic protection' of the structure, the afore-mentioned factors can make steel 'structures' have different potentials at different points. This can result to having some parts of the structure cathode and other parts anode. Once this happens, corrosion sets in.

However, if a material which has a substantially higher negative potential (less inert), such as Magnesium, Zinc or Aluminum anode or any of the alloys of the fore-going elements is positioned in close proximity to the 'structure' that is needed to be protected, be it pipeline, FPSO hull or Subsea Christmas tree, and a metallic connection (insulated wire) is placed in-between the anode and the structure, the material which has a higher negative potential gets to be the anode and the rest of the structure gets to be the cathode (Anonymous, 1985). Consequently, the new element which has a substantially higher negative potential (less inert), sacrificially corrodes to protect the rest of the structure which has been established to be the cathode. So, this approach of protecting steel structures is known as the sacrificial anode cathodic protection courtesy of the fact that the anode corrodes in sacrifice to protect rest of the structure, just as the name implies (Meillier, 2001).

For an effective deployment of anodes for 'sacrificial anode cathodic protection', certain parameters are always checked, certain experiments have to be conducted and the life pattern of the environment where the materials are to be located is also looked at critically (DNV, 2010). All components meant for 'catholic protection' with the use of the 'sacrificial anode' such as insulated wires, anode backfills and support equipment have to be readily available as part of corrosion control accepted pre-requisite or criteria (Hook, 1994).

Apart from such preparations as already been mentioned above, material selection is also key. Irrespective of the efforts we make, if the exact type of material is not chosen, the system stands to fail. Installation is also a crucial criterion to be critically considered. The improper installation of an anode could also lead to an entire system failure. There are certain preconditions that must be examined for the 'sacrificial anode protection' to be effective without abrupt retrofitting. One of such condition is the current requirement which should be less than 1 Amp, the soil resistivity which should be less than 10,00 ohm-m and when the structure has good coating criteria (Hook, 1994).

For an effective utilization of 'sacrificial anode' for 'cathodic protection', certain design considerations have mandatory priority. These mandatory considerations serving as the basis of our decision for the use of any 'sacrificial anode' (Anonymous, 1985) are: The calibrated geometry of the structure in mind to protect which is often expressed in length, width, height and diameter. They are the set of inputs used in getting the total area in terms of 'surface of structure' to protect cathodically. The facility (structure) must be drawn. Other components to be factored in are size, shape, material and location of facility that is required for protection. The structure to being protected must have electrical connection to the anode and must be isolated electrically from parts of the body of the facility not needing electrical connection. There must be assurance of thorough elimination of short-circuit from all already installed and newly installed cathodic 'protection mechanisms'. Short-circuits result in interferences with mechanisms that provide cathodic protection.

The need for finding the history of Corrosion of facilities in the vicinity of the structure is because Such studies helps to facilitate the reinforcement of corrosivity prediction of structures and that of the vicinity. There should be 'electrolyte resistivity survey'. A structure's rate of corrosion has direct effect on the electrolyte's resistivity. In an event of lack of any functional 'cathodic protection', more current flows to the electrolyte from the structure. As electrolyte resistivity decreases; corrosion rate increases. The reverse is the case, if there is increase in resistivity of electrolyte. Resistivity components are used in arriving at anode sizes as would be shown in later chapters for the determination of mechanisms for cathodic protection. A survey of the electrolyte PH has to be done. Like soil resistivity, soil PH has inverse proportionality with the electrolyte. So if soil PH decreases, the corrosion of steel corrosion increases when we have steadily maintained resistivity. 'Electrolyte survey potential' versus that of 'structure' indicates corrositvity. NACE standard No. RP-01 stipulates that the required potential for 'cathodic protection' is negative (cathode) potential of 0.85 volts at the minimum; measured with saturated Cu-$CuSO_4$ electrode which is touching the electrolyte and the facility. In a situation where there is a less negative potential which is less than -0.85 volt, the result will is corrosive with an increase in corrosivity as there is a progressive decreases in negative value.

Requirement in terms of current has to be established; as it is a critical channel for understanding procedures with respect to the volume of current required in every square meter (Current Density) to alter the facility's potential to -0.85 volt. Hence, the volume of current for every square meter demanded to create that shift in potential indicates the situation of the structure's surface (Anonymous, 1985). The extent of coating of a 'structure' determines to a great extent the volume of current in a given square meter that it would serve. For instance, a facility that has a good coating with coal-tar-epoxy requires a minimal current density of about 0.05 mA per Square meter; whereas an uncoated structure would need a higher current density of about 10mA per square meter. Ordinarily, on the average, current density for cathodic protection is 2mA for every square meter of an open location. The approach mentioned above, as a way of mitigating against corrosion, spans across a wide range of facilities by effectiveness and use: Subsea structures, Pipelines, Platforms, Wind turbine foundations, Monopoles, Wave and tidal generators, Quay and harbour walls, Jetties and pontoons, Dock gates, Ships and boat hulls, Ballast, Grey and portable water tanks, Power station intake screens, Storage tanks. Several advantages of' 'Cathodic Protection' By 'Sacrificial Anodes' exist. Wherever metals are wholly or partially immersed in water, one method than can be used in protecting such metal in water is with use of 'sacrificial anodes'. It has a number of advantages, amongst which are: Ability to cathodically protect an infrastructure for up to 25 years which happens to be the duration of service of most subsea 'structures' and indeed service life of reservoir.

There is barely any maintenance needed during the service life. They are highly reliable, they seldom need any modifications on hull interior and no hull penetrations, they rarely need interferences during use, they do not cause harm to other 'subsea' equipment and they are of high economic value because they cost less in deploying. Over all, the functionality of the protection provided by 'Sacrificial anode' is made prone to questions if they do not have proper sizing and even more so, if the mechanism for sizing is not appropriately established.

Either methods of 'cathodic protection'-'Impressed Current' or 'Sacrificial anode' are good. It depends on the type of facility put forward for protection. Be that as it may, two major fronts where the latter has higher priority compared to impressed current protection is in simplicity of deployment, mechanism and reliability (Callon, 2006). Other advantages are cost effectiveness in some circumstances and also need fewer components than that of impressed current (Paul, 2014). Another major area of advantage over other forms of protection is concerns on the issue of likelihood of interference. Furthermore, 'Galvanic cathodic protection' are mostly distributed in nature. This feature is of immense significance because of the limited potentials of the components the anodes are made of on the other hand, 'Sacrificial Anode Cathodic Protection' has its disadvantages. The cardinal minus of using sacrificial anode approach to protect facilities is linked to insufficient potential between the facility to be protected and the anode in use. This to an extent, limits the current discharged from the anode and further has a restricting impact on the extent of protection to be provided by the anode. (NME Group, 2017). More so, despite the performance delivered over time of anodes, there always has to be provision for intermittent replacement during use as a preemptive step for a failure-free service life. Ultimately, for avoidance of frequent anode retrofitting, sufficient anode materials are put in place in other that interval for replacement for design life which is 25 years for this project (Osvoll, 2006). In cases where the facility is subsea or buried and as such retrofitting is cumbersome, the replacement interval could be up 25-30 years which could indeed be the life of the facility according to design.

## II. LITERATURE REVIEW

A process which allows current to move from an electropositive side (anode) of a metal through a solution (an electrolyte) and enters the metal through the electronegative side (cathode) site which is electrochemical in nature is called corrosion (Anonymous, 1985).

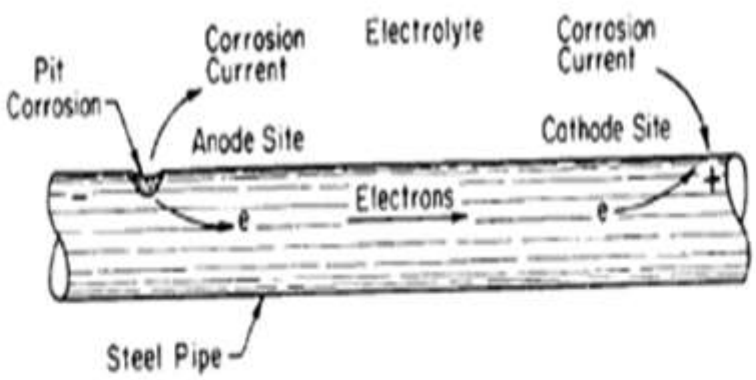



Figure 2.1: Corrosion of Pipeline. Source: Apelgate (1960)

### 1) Corrosion of Steel in Water

For occurrence of corrosion, three items are in focus: There must be two varying types of metals, there must be an electrolyte consisting water and any type of salt or dissolved salts and the two varying metals must be connected. Chemically, the above phenomenon could be better explained using the famous relations of corrosion. Basically, two reactions occur in an event of corrosion. Oxidation Reactions at the anode side involve oxidation of metal to its ions. The oxidation reaction for steel is:

$Fe > Fe^{2+} + 2e$ (2.1)

Whereas the other end involves reduction. However, acid water, with plenty of hydrogen ions ($H^+$) holds the reaction below:

$2H^+ + 2e > H_2$ (2.2)

In the absence of hydrogen ions, the removal of water result in the liberation of alkaline and hydrogen.

$2H_2O + 2e > H_2 + 2OH^-$ (2. 3)

If the water does not de-aerate, oxygen reduction is expectant process. Thereby producing alkaline at surface of metal.

$O_2 + 2H_2O + 4e > 4OH^2$ (2. 4)

The two reactions can be changed by simply withdrawing or adding electrons. Correspondingly, withdrawal from a metal of electrons creates a surge reaction rate in equation 1 which will in turn tend to offset the process and speed up the dissolving of ion; whereas reaction 2 decreases. In the contrary sense, adding more electrons from a different source to the metal will decrease reaction 1 which eventually results to decrease in corrosion. Reaction 2 decrease as a result (Shashi, 2012).

Corrosion is a devastating phenomenon to the live of metals; whether offshore or onshore, in the Oil and Gas industries. The loss or deterioration of metals which we term corrosion is basically caused by electrochemical reactions (Anonymous, 1985). Studies have shown that corrosion costs the US government alone, above $ 276 billion yearly (Anonymous, 1985). To a great extent, corrosion can now be substantially reduced or mitigated using different technological approaches and methodologies.

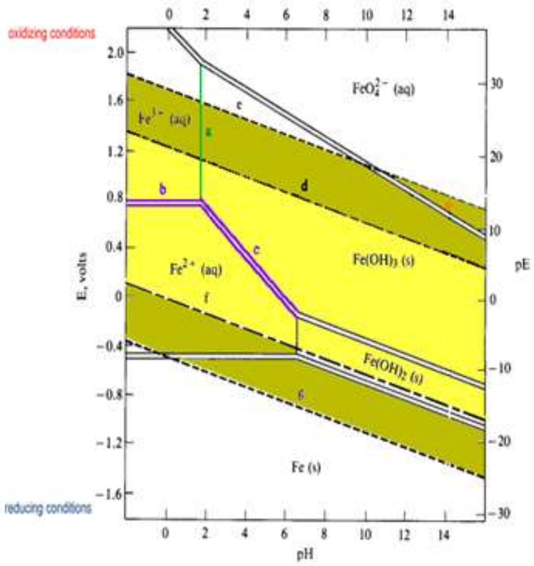
2) **2.3 Mitigating steel corrosion in water**

Though, there are a number of methods of mitigating or putting corrosion under check. Never the less, achieving control over corrosion with use of Cathodic Protection technique has a high level of credibility. This approach was deployed in 1824 by Sir Humphrey Davy and narrated in papers which were presented to the Royal Society (Humphrey, 1824) in London. Simply by making a metal surface the cathode of an electrochemical cell, that metal can be protected (NACE RP0176). Such methodology is used in protecting quite a number of materials. These structures include steel, Flowlines, pipes, tanks, onshore and offshore platforms, ship and FPSO hulls, onshore and offshore well casings, risers and umbilical etc. (anonymous, 1996). After the immense contribution of Davy in the 1820s, a faster pace of use and improvement of cathodic protections soared in the United States to satisfy the needs of an ever expanding exploration and exploitation business (Francis, 2004).

The list of the corrosion of steel in soil or seawater against soil resistivity is shown in Table 2.1.

Table 2.1: Corrosion of Steel in Soil/Water Based on Soil Resistivity

| Range of Resistivity of Soil (Ohm-cm) | Corrosivity |
|---|---|
| 0 to 2000 | Severe |
| 2000 -10,000 | Moderate |
| 10,000 - 30,000 | Mild |
| 30,000 and higher | Not Likely |




Source: U.S Air Force (2016)

The first instance of protection of facilities which was cathodic that involved the principles and techniques concerning cathodic protection was first put forward by Sir Humphrey Davy (1778-1829) in 1824 (Juárez2, 2000). Being a scientist and an experimentalist who lived in first part of the 19th century, he used galvanic cells similar to the ones which were used by Alessandro Volta in the 1790s to produce electricity (Pipeliner, 2016). He was able to stall the rapid disintegration of copper by way of using minute particles of zinc, or iron nails which were attached on the protective copper sheath installed on a structure such as the hull of a wooden warship (Juárez2, 2000). Without the exposure of steel to the environment that can conduct electrolysis, cathodic protection will not succeed. Therefore, the proof of feasibility of the technique shown in this book is only obtainable in aqueous environment. That notwithstanding, cathodic protection is also possible in moist and sandy soils.

Before Davy's work gained acceptance in 1824, by the Royal Navy, he had long around 1806 advanced the possible identical nature of electro-chemical charges in a hypothesis and had been able to convince a Swedish Chemist called Berzelius (Pipeliner, 2016).

Cathodic protection is electrochemical protection by minimization of a metal's corrosion potential to a level where it is almost eliminated (ISO 8044).
The work by Davy informed the body of science of two principal ways to arrive at cathodic protection. One of

which is sacrificial anode and another is impressed current using a DC power supply. Either approach tends to move the potential of the metal we intend to protect to the negative. With sufficient current to maintain the needed polarization, the anode is consumed; whereas the cathode is not.

Michael Faraday's work on comparing electricity and corrosion which further proved their electrochemical equivalence followed the efforts of Davy. Also, Josiah Gibb used the idea of thermodynamics to substantiate Davy. During the 1890s and 1900s, Julius Tafel's idea of the regulation of the anodic and cathodic reaction rates was as a result of the investigation of how it was because of changes in metal potentials (Pipeliner, 2016).

Walter Nernst showed that the calculation of the potential of a metal could be done if the knowledge of the concentrations of reactants and products were known and by so doing, also demonstrated the modalities for the prediction of the stability of chemical species if the potential and PH were also established.

A summary of all the features were put into a diagram called the Pourbaix diagrams by Marcel Pourbaix in 1945. In addition, a clear kinetic narrative of cathodic protection that is valid till date was put forward by R.B Mears and R.H. Brown.

Figure 2.2: Simplified Pourbaix diagram for 1 M iron solutions
Source: https://www.wou.edu/las/physci/ch412/pourbaix.htm (2014)

1) **Cathodic Protections to Pipelines**

By the 1920s, 'cathodic protection' utilizing zinc 'sacrificial anodes' had become increasingly deployed in pipelines and shipping industries. The 'United States of America', had one of the foremost pioneers of 'impressed current' transformer rectifier in 1928 for protecting of long-distance pipeline was Robert J. Kuhn. This was in New Orleans (Pipeliner, 2016). In continuation of his wide range field test, he was able to establish that a potential shift to -0.85 volts relative to $Cu/CuSO_4$ reference electrode provided the optimum protection for soils that have ferrous 'structures'. There was suitability for steel for this criteria not only underground but in seawater.

The advancement of practical application of Cathodic Protection is common place in many parts of the world. Australia seems to feature strongly (Pipeliner, 2016). William Alexander Johnson, was an Australian and one of the early major contributors to advance the concept of cathodic protection; especially in Australia. Owing to his enormous contributions, a biography was published by Brian Hatfield. Not only was he acknowledged by the 'Australian government', he was nominated by 'Australian government' as officer in charge of electrolysis for Melbourne and Metropolitan Board of Works (MMBW) in 1928 (Pipeliner, 2016). As a Metropolitan city, Melbourne had countless issues associated with effects of DC traction systems and considerable work was conducted to fight mitigate the electrolysis that resulted from the activities of trains and trams. Today, Australia ranks amongst the top in 'cathodic protection' mechanisms.

Quite a range of structures, ranging from wharves, jetties, ships, well casings, pipelines, storage tanks, offshore platforms and vessels, subsea equipment including Christmas trees and lots more now have success in applying 'cathodic protection' on them (Pipeliner, 2016).

The effectiveness of 'cathodic protection' of steel in soils was also meaningfully established around 1940 (Sagüés, 2005). The establishment of the unique efficacy of 'cathodic protection' of steel in soil was manifested when 'cathodic protection' was used on an already existing natural gas pitting network which had already developed leaks at an ever increasing pace to an extent that the decision for abandonment was already in the offing. There was a great decline in the quantity of leak the moment 'cathodic protection' was installed (Sagüés, 2005).

In modern times, actively sailing ships had specifications meant for 'cathodic protection' initially around 1950 (NME, 2016). From then on, an increase in trend in the progress made in 'cathodic protection' utilizing 'sacrificial anode' system set in. Consequently, upon constant work and commitment, better 'sacrificial anode' materials are being used and more technologies emanating.

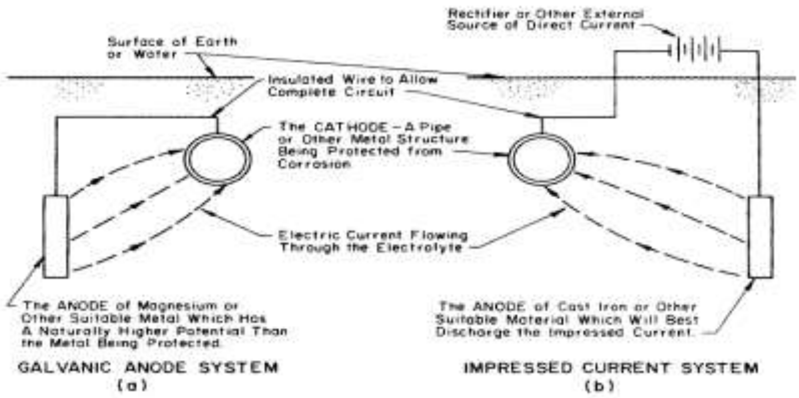



*Figure 2.3:''galvanic anode' and 'impressed current cathodic protection system''*

1) **2.5 Principle of 'Sacrificial Anode Cathodic Protection'**

Sacrificial anodes work on the principle similar to electrolysis, according to which if an anode and a metallic strip are dipped in electrolytic solution, anode electron will dissolve and deposit over the metallic strip and make it a cathode (Anish, 2016)

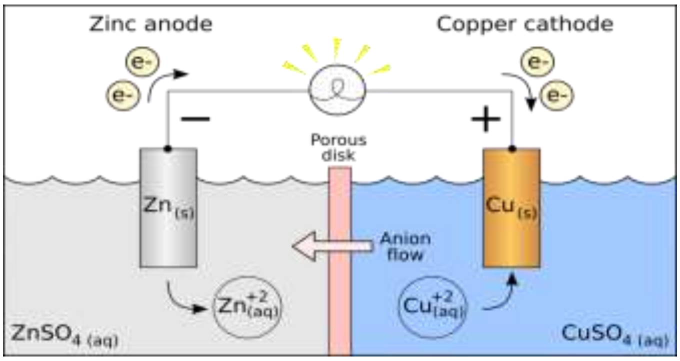



Figure 2.4: “Principle of sacrificial anode cathodic protection”. Source: Ohiostandard (2011)

For ships, ‘seawater’ becomes the ‘electrolyte’ and transfers the ‘electrons’ from the anode by oxidizing it over the steel and making a protecting layer. In an event of the metal being more active ‘oxidation’ occurs and protects the metallic compound by making the cathode. The anode will corrode first sacrificing itself. This is called sacrificial anode (Anish, 2016).

## III. METHODOLOGY

### 3.1 Programming Approach

The idea of this project is to build a software (application) that sizes sacrificial anodes materials ( Zn, Al and Mg) for ‘cathodic protection’ jumper and flowline manifold end side fitting, ‘subsea’ with the objective of creating a students’ anode sizing software that could be used for class room practice in Nigerian Universities and also for the ‘Oil and Gas Industry’. The work will assist in the estimation of anode material used in ‘Chevron Agbami Offshore’ the Niger Delta Area of Nigeria. Class room sizing of anodes, for estimation of service life of ‘sacrificial anodes’ is usually done by hand calculation. But this approach seems cumbersome and subject to mistakes because of human error in calculation. Therefore, this software is built to enhance accuracy of result, safe time and usher in a better grasp of anode sizing using computer software.

The programming language used in building this ‘software’ is Java Language. After the development, the results gotten by the software is matched with output of the sizing estimation of the ‘Chevron Nigeria Limited Agbami’ Offshore subsea Oil field for software result validation. Additional functionality like over/under designing will also be compared to see the level of accuracy of the software. To be able to establishment ‘cathodic protection’, an absolute grasp of the ‘structure’ is key. The items in focus are: structure, Location, Protection criteria, cathodic protection Current Demands, Cathodic Protection Type, and Anode Type Selection. Other parameters are: ‘Structure’ Type, operating conditions of ‘structure’, Geometry and surface area of the structure, Determine coating status of ‘structure’, Pre-existing data from previous systems of ‘cathodic protections’, ‘Design life of the structure’.

### 3.2 Software Programming Algorithm

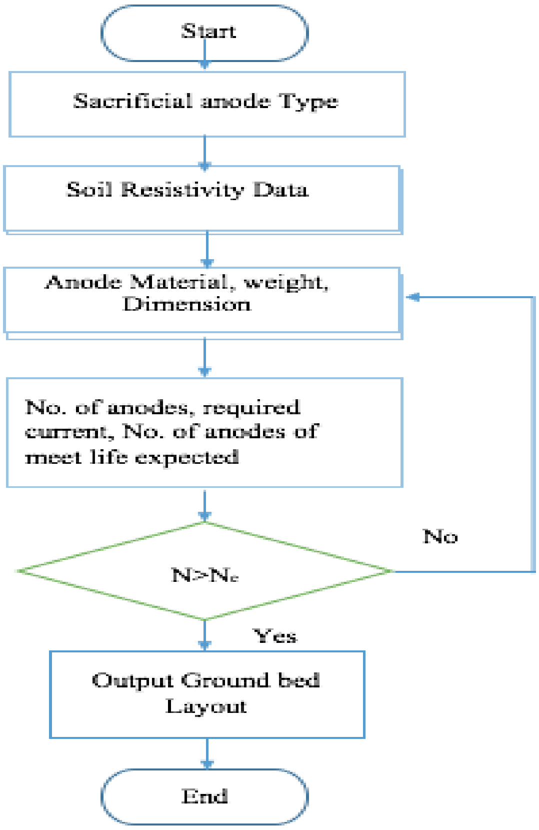



Figure 3.1: Work Flow Chart for Software Programming

Before the procedures highlighted above are imputed, certain parameters and criteria must be consideration. They are: The grade of the pipe we want to protect is x42.

### 3.3 The Usefulness of High Level Programming Languages

Programming languages are today proven to be formal languages comprising of a set of instructions used for producing different outputs (Krishnamurthi, 2017). These outputs could be used in computers for different applications. Programming languages generate programs that are used to implement algorithms. Albeit there have been programming machines before now, programming languages are more widely used in computers. As a result, people now call it computer languages. There are various computer languages but few are widely useful. Majorly, there are 2 categories of programming Languages: The Low and High Level Programming Languages (Krishnamurthi, 2017). The low level programming languages are basically Machine Language and Assembly language. Low level programming languages always require thorough or absolute intervention and skill of the programmer to manage the features and operation of the program. On the contrary, High Level Programming Levels Languages shield the programmers from getting to meddle with the nitty-gritties of the operation of the Program and ultimately the execution of the codes written in the computer (Britannica Encyclopedia, 2017).

As has been mentioned in the earlier part of this chapter, there are different types of programming languages depending on the application we want to deploy. Since this work would make use of High Level Programming Language, few examples of such languages are: Java, C, C++, C # (C sharp), Python, PHP, SQL, FORTRAN, COBALT, LISP, RUBY etc. some of these languages have wide use in the application of Operating Systems (OS) such as Windows OS, Mac OS, Android and others. Few others have great application in web development and e-commerce or enterprise applications. C#, JavaScript and Python have great inheritance and attributes of C, which is used for operating systems and embedded applications.

### 3.3.1 Java Programming Language

Java Programming language was used to write the codes for the anode sizing software. Java is a high level programming language developed by Sun Microsystems, which allows the programmer to write the codes and then goes ahead to carry out processes to completion by way of outputting the results (David J Eck, 2006). The uniqueness of Java and its relevance in use here is for several reasons. As has already been established, Java is concurrent, class-based, and object-oriented. Its use in a variety of systems; be it music, gaming, banking, web development, big data, Operating Systems and lots more, makes it a robust tool for programming (David J Eck, 2006). Unlike other programming languages, java is free to access and it is adaptable on a myriad of platforms. The afore-mentioned advantages will give the application the flexibility to be used in other platforms without the need for recompilation.

### 3.4 Conditions for Programming

The programming and subsequent output of results put few conditions into consideration, as it would be done in real life scenario. They are:

Net initial driving potential between sacrificial anode and cathode is estimated using the equation $E= E_a-E_e$ ($E$=Net driving potential; $E_a$=Anode driving potential; $E_e$= Average steel pipeline potential)
The area of the structure to be protected is small as far as the protection methodology is Sacrificial anode Cathodic Protection.
The resistivity of the soil is low
The structure to be protected is not coated.
The driving potential volt with reference to Copper-Copper sulfate is given by -1.55 Volts.
The environment of protection is seawater.
Potential is seawater is -0.68volts
The structure to be coated is a pipeline.

### 3.5 The Agbami Oil Field Description

The Agbami Oil field is 1400-1550m subsea offshore the coast of Nigeria between offshore prospecting lease (OPL) 216 and 217 at approximately 220 nautical miles southeast of Lagos. The subsea production and injection wells are connected to a FPSO via subsea manifolds with static and dynamic umbilicals, flexical risers, flowlines and jumpers. Treated stabilized crude oil will be offloaded from the FPSO from time to time through mid-water offloading line between the FPSO and a Single Point Mooring Buoy (SPMB).

### 3.5.1 The Cathodic Protection for the Agbami Oil Filed

Cathodic protection of flexible risers and Christmas Trees (XT), is done by the use of Sacrificial Anodes (SA) mounted on the vicinity of end fittings. None the less, some sacrificial anodes were installed by the Subsea Equipment Vendor (SEV) for the protection of some flexible flowlines by being mounted on the adjacent subsea structures. The properties of the sacrificial anodes are such that it does not cause adverse effects on impacts negatively on the environment (ISO 14001). And the components supplied do not have heavy metals (ISO 14001).

### *3.6 Anode Geometry*

The anode geometry refers to the shape and design of the anodes used in the cathodic protection of offshore structures.

### 3.6.1 The Anodic configurations and designs

The basic design and configuration for offshore applications are:
Slender stand-off
Elongated, flush mounted
Bracelet

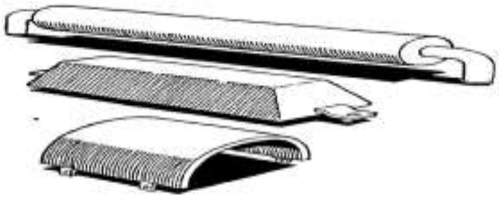


Figure 3.2 "Geometric Configuration of Anode Plates". Source: DNV RP401 (1993)

**3.6.2 Basis for Configuration or Designs**

The design used in any case is usually specified by the operator and should put into consideration the following factors:
The utilization of the anode and the output of current
The constrains for installation and processes for intervention subsea.
The weight force and drag force that can be exerted by subsea currents.
The financial implications of manufacture and installation.
The ability of the anode design to be easily accessible to diver hoses or ROV umbilical's.

**3.7 The Sacrificial Anode Materials**

Typically, sacrificial anodes used in offshore installations are majorly either Aluminium or Zinc. However, operators have the prerogative to choose or specify what type of anode materials they want to use. Aluminium based anode materials are often times preferred over other times owing to their electrochemical efficiency. Magnesium based anode materials have also been used in combination with Aluminium based materials in other to achieve rapid polarization during the beginning phase. It is important to note that the specification and consequent use of any type of anode material depends on the experience of the operator with that type of anode material. This could depend on long-term testing. The anode materials used in this work at the Chevron Agbami Oil field and the other which will be used for comparison purposes are Aluninium and Magnesium based alloys.

**3.7.1 Recommended Maximum level of Impurity content**

The recommended maximum quantity or level of impurities that an anode material should have that could be used for testing procedure for long-term testing of anode materials is shown in the table below:

Table 3.1: Recommended Maximum Quantity or Level of Impurities of an Anode Material

| Impurity Element | Maximum Content (% weight) | |
|---|---|---|
| | Zn-base | Al-base |
| Fe | 0.005 | 0.10 |
| Cu | 0.005 | 0.006 |
| Pb | 0.006 | - |
| Si | 0.12 | 0.15 |

Source: DNV RP-01(2015)

### 3.7.2 The Aluminum Alloy Anode

The sacrificial anode material is an alloy of Aluminum. This type of alloy is widely used in offshore applications for pipelines containing products at high temperatures. The purity of the anode material (raw Aluminum) is not less than 99.8% (by weight). No anode was poured from scrap aluminum or recycled

The Chemical Composition of the Anode is covered in table 3.2

Table 3.2: Aluminum Anode Composition

| Elements | Weight (%) |
|---|---|
| Zinc | 4.75-5.75 |
| Indium | 0.016-0.020 |
| Silicon | 0.08-0.12 |
| Iron | 0.06 |
| Copper | 0.003 |
| Cadmium | 0.002 |
| Other elements | 0.02 each |
| Total Other elements | 0.05 |
| Aluminum | Balance |

Source: AGB-SPECS, AGB-TEF-IR-SPC-FL-6105-00 (2013)

Note: No additions other than zinc, indium or silicon are allowed and all values are maximums unless otherwise allowed.

In as much as we want to see how accurate this software works, it is necessary to target a section of the flowline that can be easily worked on. Our focus is flexible flowline end fittings. The field data of such flexible flowline end fitting is shown below:

Table 3.3: Predefined Anode Sizing parameters for Production Flexible Flowline

| Anode Location | Anode Type Number | Inner Diameter (m) | Max Length (m | Thickness (m) | Exposed Surface ($m^2$) | Weight (Kg) |
|---|---|---|---|---|---|---|
| Production Riser Bottom End Fitting | 1 | 0.520 | 0.3 | 0.5 | 0.68 | 70 |
| Production Main Flowline Riser Side End Fitting | 2 | 0.500 | 0.3 | 0.05 | 0.66 | 68 |
| Production Main Flowline Manifold side End Fitting | 2 | 0.500 | 0.3 | 0.05 | 0.66 | 68 |
| Production Infield Flowline end Fitting | 3 | 0.490 | 0.3 | 0.05 | 0.65 | 67 |
| Production Tree Flowline | 4 | 0.370 | 0.25 | 0.05 | 0.44 | 43 |

| | | | | | | |
|---|---|---|---|---|---|---|
| End Fitting | | | | | | |
| Production Jumper End Fitting | 5 | 0.420 | 0.15 | 0.07 | 0.38 | 43 |
| Riser | 6 | 0.410 | 0.4 | 0.05 | 0.72 | 76 |

Source: Subsea Installation, AGB-C-03-035 (2013

Table 3.4 gives us an impression of the number of anodes per flowline as required:

Table 3.4: Quantity of the Required Anodes for Production Lines

| Production Line Locations | Length/Surface To be Processed ($m/m^2$) | Anode Type Number | Number of Anodes | Spares |
|---|---|---|---|---|
| 8x Production Riser Bottom End Fitting | 2.8 $m^2$ | 1 | 8x1 | 1 |
| 8x Production Main Flowline Riser Side End Fitting | 2.2 $m^2$ | 2 | 8x1 | 2 |
| 8xProduction Main Flowline Manifold Side end Fitting | 2.2 $m^2$ | 2 | 8x1 | - |
| 4x2xProduction Infield Flowline End Fitting | 2.1 $m^2$ | 3 | 4x2x1 | 1 |
| 2x2xProduction Tree Flowline End Fittings | 1.1 $m^2$ | 4 | 2x2x1 | 1 |
| 10x2xProduction Jumper End Fittings | 1.5 $m^2$ | 5 | 10x2x1 | 3 |
| 8x Riser @ Riser/Flowline Connection | 8x2000m | 6 | 8x6 | 7 |
| PMA-1 Main Flowline @ Riser/Flowline Connection | 510m | 6 | 1 | - |
| PMA-2 Main Flowline @ Riser/Flowline Connection | 519m | 6 | 1 | - |
| PMD-1 Main Flowline @ Riser/Flowline Connection | 825m | 6 | 1 | - |
| PMD-2 Main Flowline @ Riser/Flowline Connection | 824m | 6 | 1 | - |
| PMF-1 Main Flowline @ Riser/Flowline Connection | 1235m | 6 | 3 | - |

| | | | | |
|---|---|---|---|---|
| PMF-2 Main Flowline @ Riser/Flowline Connection | 1235m | 6 | 3 | - |
| PMG-1 Main Flowline @ Riser/Flowline Connection | 381m | 6 | 1 | - |
| PMG-2 Main Flowline @ Riser/Flowline Connection | 376m | 6 | 1 | - |

Source: Subsea Installation, AGB-C-03-035 (2013)

#### 3.7.2.1 Electrochemical Properties

The considered potential of anode in seawater with respect to Ag/AgCl is -1050mV and the current density depends on the temperature of the anode. For every degree rise above 25°C, there is a corresponding increase by mA/$m^2$ of the current density. This is with reference to current density given below:

Initial (polarization) current density ($H_2O$) is 321mA/$m^2$

Average (maintenance) current density ($H_2O$) is 108mA/$m^2$

Final current density ($H_2O$) is 129mA/$m^2$

The considered anode current capacity for seawater is 2381 A-hr/kg

The utilization factor depends on the shape of the anode. For bracelet anodes, the utilization factor is 0.80 cf /B13/. The cathodic protection design is done with bracelet anodes on pipes that are flexible and kept in the vicinity of end fittings. Two-part welded carbon steel clamp serves as a base for the anode to be mounted on. Below is a drawing that shows how it looks:

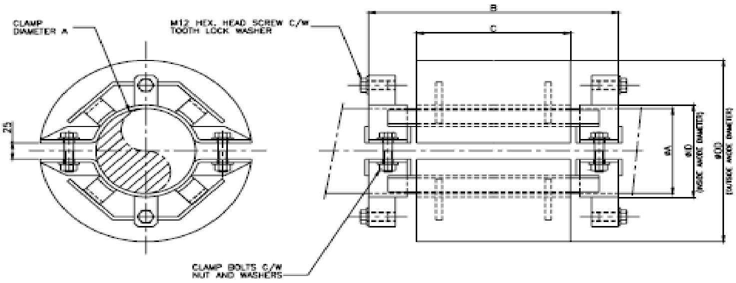



Figure 3.3: "Bracelet Anode Typical Drawing". Source: Design Basis, Doc No. M40109 (2013) *3.7.2.2 Weight and Dimension Tolerances*

The weight of the anodes is estimated as net weights which excludes anode supports and core. weight tolerance on the individual anodes is -0% to +5% of design net weight. Additional parameters of the anode are:

Internal diameter of anode is -0 to 3.17mm (1/8 inch)

Width (length) of anode is $\pm 2.5\%$ and 25.4mm (1 inch)

Thickness of anode is $\pm 3$mm

Weight of alloy is 18.14kg with a tolerance of not more than 2%

3.7.3 The Magnesium Alloy Anode

The properties of the Magnesium Alloy used as an anode which will be used for comparison in this work is as follows:

The current density of the Magnesium anode is: 25mA/$m^2$

The dimensions of the anode expressed in Length (L), Breadth (B) and Height (H) is: (LxBxH) in meters. It is given as (0.67x0.67x 3.5) m

The Magnesium Alloy consumption rate is: 4kg/Amp-yrs (Kilogram/ Ampere-Years)

The Potential with reference to $Cu/CuSO_4$ is: -1.55 volts
The electrochemical capacity of the anode is: 1230Amp Hr/kg (Ampere Hour/kilogram)
The weight of the Magnesium anode is: 25Kg (kilogram). This weight is a summation of all the other components that make up the alloy.
The utilization Factor of the alloy is: 0.85
The pipeline joint length is approximately 27m
Other vital details regarding essential data of the alloy to be used are that:

The potential in seawater needs a minimum of -0.68volts ((DNV, 2010)
The pipeline will catholically polarize with a minimum of -0.85 with reference to Cupper/Cupper Sulfate ($Cu/CuSO_2$).

**3.8 The Properties of the Structure to be protected (pipe grade of the structure is x42)**

The Properties of jumpers are shown in Table 3.5.

Table 3.5: Jumper Properties

| | |
|---|---|
| Pipe Diameter | 0.15 m |
| Pipeline Length in seawater in mud | 0 |
| Length of pipeline in seawater | 27.432m |
| Length of pipeline in mud | 0 |
| current density in seawater | 21mA/m$^2$ |
| Average current density in mud | 0 |
| Coating coefficient | 0.9 |
| Design Life | 25 years |
| Pipeline Joint Length | 0 |

Source: Design Basis, Doc No. M40109 (2014)

**3.9 Calculation for Magnesium Alloy Anode**

The potential in seawater needs minimum of -0.68 volts (standard) and the net driving potential between sacrificial anode and cathode is estimated by formula shown as used in the calculation for potentials. More so, it is also important to note that pipeline will cathodically polarize with minimum of -0.85 with reference to copper/ Copper Sulfate (DNV, 2010).

E – Net driving Force; $E_a$ – Anode Driving Force and $E_c$ – Average steel pipeline Potential

Net Initial driving force, expressed as E is:

$$E = E_a - E_c \quad (3.1)$$

$$E = -1.55 - (-0.68) = -0.87 \ volts$$

Net Final Driving Force, expressed as E is:

$$E = E_a - E_c \quad (3.\ 2)$$

$$E = -1.55 - (-0.85) = -0.7 \ volts$$

a) Total External Surface ($S_a$) is:

$$S_a = \pi * d * l * f_c \quad (3.3)$$

d- Diameter of pipe; l- Length of pipe; fc- coefficient factor

b) **3.10 Resistivity difference between seawater $I_r$ is:**

The Lowest resistivity could be 0.3ohm meter and any decrease in resistivity has an increase in corrosion.

Resistivity ($I_r$) = $S_a$ * Average Current density in seawater (3.4)

c) Resistance to earth ($R_v$) is:

$$R_v = 0.00512 * I_r * \left(\frac{[\ln(\{(8*3.5)/0.67\})-1]}{3.5}\right) \quad (3.5)$$

d) Current Output per anode ($I_a$) is:

$$I_a = \frac{E}{R_v}\text{b} \quad (3.6)$$

Design Life of Anode ($d_a$) is:

$$d_a = \frac{M*u*\varepsilon}{I_a*8760} \quad (3.7)$$

Design life is expressed in years. The number 8760 is a year expressed in hours. In the formula shown above:

M- total net weight of the sacrificial anode to protect pipe; u is the utilization factor and $\varepsilon$ is the electrochemical factor of the anode.

Total net weight of sacrificial anode to protect pipe (M) is:

$$M = \frac{I_c*d_l*8760}{u*\varepsilon} \quad (3.9)$$

Total net weight is calculated in kilogram (kg)

Number of Anodes to meet intended design life ($N_a$) is:

$$N_a = \frac{d_a*I_r}{1000*Current\ Density} \quad (3.10)$$

$$N_a = \frac{40*2262240}{1000*25} \quad (3.\ 11)$$

Anode Spacing to determine linear distance of anode arrangement

$$A_s = \frac{Pipeline\ Length\ in\ seawater}{N_a} \quad (3.12)$$

Anode spacing is expressed in meters

e) Interval of pipe Joint

$$interval = \frac{A_s}{Pipe\ joint\ length\ in\ joints} \quad (3.13)$$

f) Ground bed selection ($P_a$) is: $P_a = \frac{S_a}{N_a}$ (3.14)

Location prepared to keep either single or a combination of anodes is most protection area.

g) **3.11 The Magnesium Alloy Material Properties**

Table 3.6 shows the properties of the second anode material (Magnesium alloy) which will be used to compare with the Aluminum Alloy.

Table 3.6: Magnesium Anode Properties

| Quantity | Value | Unit |
|---|---|---|
| Current density | 21 | mA/m$^2$ |
| Dimension of Anode in meters (L*B*H) | (0.67*0.67*3.5) | m |
| Mg Alloy Consumption Rate | 4 | kg/Amp-yr |
| Potential with reference to $CuSO_4$ | -0.85 | volts |
| Electrochemical Capacity of Anode | 1230 | Amp-hr/kg |

| | | |
|---|---|---|
| Weight of Anode | 18.14 | kg |
| Utilization factor | 0.85 | |

Source: BS EN 10204 (2014)

2) **3.12 Approach to Programming**

For the Aluminum anode, the parameters used are those that were used by the Agbami Filed project while the anode that would be used for the comparison, in this case the Magnesium anode will assume standard Magnesium anode parameters already established based on projects and as stipulated by codes and standards for anode installation.

a) **3.12.1 Input Method of Environmental Data**

The environmental data where the anode is to be installed to a great extent determines the type of anode to be used. So after the program code is written, the running of the software pops up a window that has provision for the environmental data that will have been included by default.

After the type or environment where anode is to be installed is established, in this case seawater, we further identify certain characteristics of the environment. Parameters such as resistivity, PH, acidity, temperature, pressure etc. are entered into the program. This is because, these are parameters take are required later on in the program to be used in the calculations to determine anode characteristics.

b) **3.12.2 Input Method for parameters of Structure to be protected**

The second step in the programming is the input of the parameters or properties of the structure to be protected; as they will further be used for the calculation of anode properties that will be used for our comparison for which anode is best for that environment. In this section of the interface, the user has provision to enter details of the anode. Since the structure to be protected in our case is a pipeline, we would enter the data as follows:

Diameter (m)
Pipeline Length in seawater in mud (m)
Length of pipeline in seawater (m)
Length of pipeline in mud (m)
Average current density in seawater (mA/$m^2$)
Average current density in mud (mA/$m^2$)
Coating coefficient
Design life
Pipeline Joint Length (m)

c) **3.12.3 Input Method for Properties of First Anode Material**

Anode Material (Mg)
Current Density in mA/$m^2$
Dimensions of anode in meters
Consumption Rate of the Anode or Alloy in Kg/Am-yr
Potential with $CuSO_4$, taken by standard to be -1.55volts for Magnesium
Electrochemical capacity of anode given as 1230 Amp-hr/Kg
Weight of Anode (Kg)
Utilization Factor given as 0.85

d) **3.12.4 Input Method for Properties of Second Anode Material**

Anode Material (Al)

Current Density in mA/$m^2$
Dimensions of anode in meters
Consumption Rate of the Anode or Alloy in Kg/Am-yr
Potential with $CuSO_4$, taken by standard to be -1.55volts for Magnesium
Electrochemical capacity of anode given as 1230 Amp-hr/Kg
Weight of Anode (Kg)
Utilization Factor given as 0.85

#### 3.12.4 Expected Outcome

The outcome or result of the software when run will be a display of two tables. The tables will have parameters of each of the anodes. These properties are as a result of calculation that have been made in the code: the output will be the following items:

- The Net driving potential
- Total external surface area
- Resistivity
- Resistance to earth
- Current output per anode
- Design life of anode
- Number of anodes to meet intended design life of pipeline
- Anode spacing to determine linear distance of anode arrangement
- Interval of pipe joint
- Ground selection for most protection area.

The two tables could be used for comparison to determine which of the anodes with reference to the environmental data best serves the purpose of protection of structure and service life of the anode. The software is programmed such that even graphs could be generated to show some basic patterns of an anode's property preferences over another.

## IV. RESULTS AND DISCUSSIONS

### 4.1 Results

The development of the software for sacrificial anode sizing was done using three components. They are: DB Browser for SQLite; Eclipse IDE; and Java. The DB Browser for SQLite serves as a database for record keeping, while the Eclipse IDE is the platform for handling the Java programming language. The DB browser is shown in Figure 4.1.

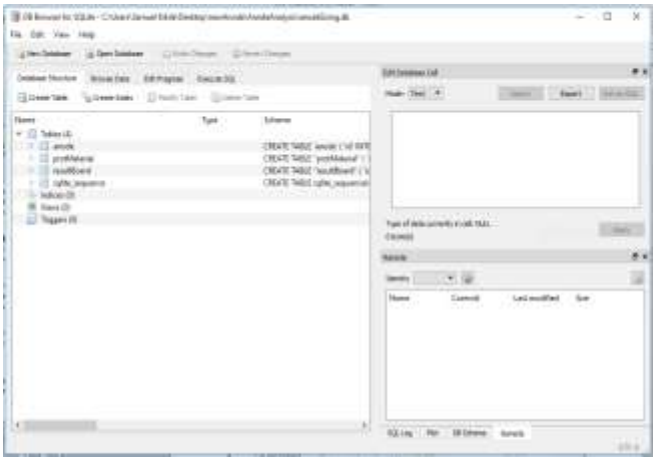


Figure 4.1: DB Browser for SQLite

The data inputted into the DB browser could be seen in a tabular form as shown in Figure 4.2.

Figure 4.2: DB Browser for SQLite showing database table

The Java programming language was coded on the ECLIPSE IDE platform which supports easy manipulation of data and also gave the work the possibility of tabulating data in a clear and concise format.

After the software code is written within the Eclipse IDE environment, it offers us the opportunity to view source code within the IDE environment and also gives us the possibility to view our software code section-by-section as shown in Figure in 4.3.

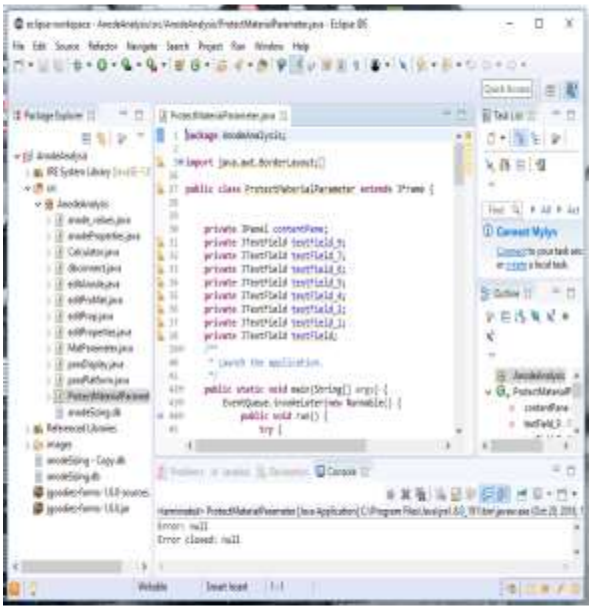


Figure 4.3: Eclipse IDE work Space Interface showing Java code

After the programme code was written in Java language, it was then exported to a format where a desktop icon of the software could be created. However, a click of the run button on the eclipse IDE interface produces the Software interface for further analysis to be done. The environment of the Eclipse at this stage is a black screen as shown in Figure 4.4

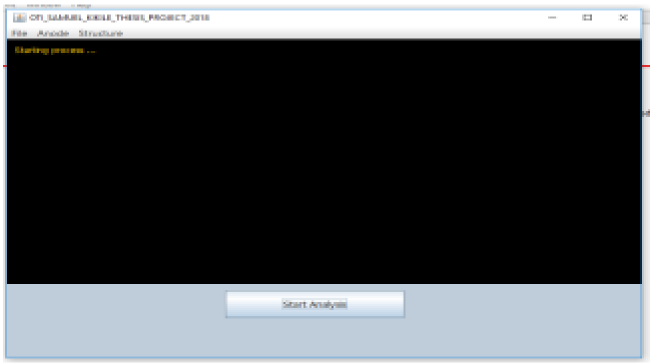



Figure 4.4: First interface of the anode sizing software.

The uppermost or top most part of the first interface, like most other software, bears the title of the software “OTI_SAMUEL_KIKILE_THESIS_PROJECT_2018”. The second bar contains three items: File; Anode and Structure.

File: the file menu simply gives us the possibility to exit the software main console. Anode: the anode menu gives room for populating anode properties Structure: this menu gives room for updating structure properties. A click on the anode type; be it Aluminum, Zinc or Magnesium, brings up two menus: the” update anode” and “new anode”. A click on the ‘update’ gives the possibility of correcting or editing any wrong information that may have been entered before. Whereas, the ‘new anode’ option deals primarily with entirely new anode types.
A click on the update anode menu pops up figure 4.5

Figure 4.5: Anode Update Window

Furthermore, if the ‘show material ‘button is clicked, a form where different anode properties could be entered comes on. This form is shown in Figure 4.6

*Figure 4.6: window of new anode Properties Input*

The lower part of the first interface software window contains the “Start Anlysis” menu which gives us the possibility of entering the data of the structure to be protected and analyzing them as shown in Figure 4.7.

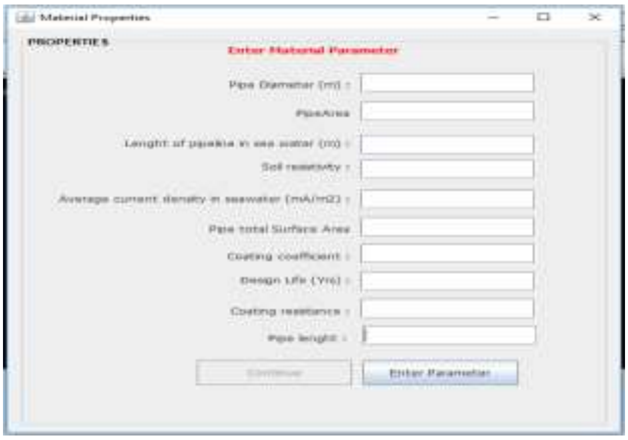


Figure 4.7: Window for data analysis of Material Parameters

When data is inputted into the new anode material, for anode properties, a showing the properties of anode material leads to figure 4.8

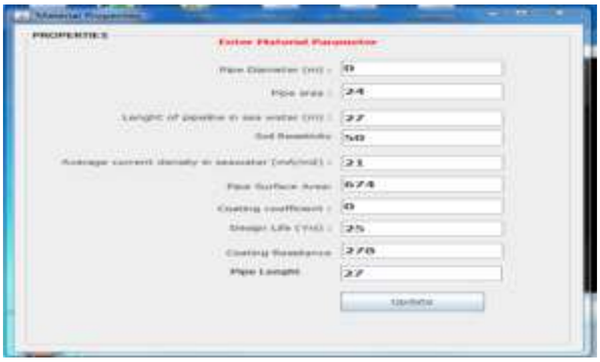


Figure 4.8: Inputted Parameters of Mg anode material

After the data is entered on the Eclipse IDE environment, it goes straight to the Database and can see seen and appreciated as shown as figure 4.9.

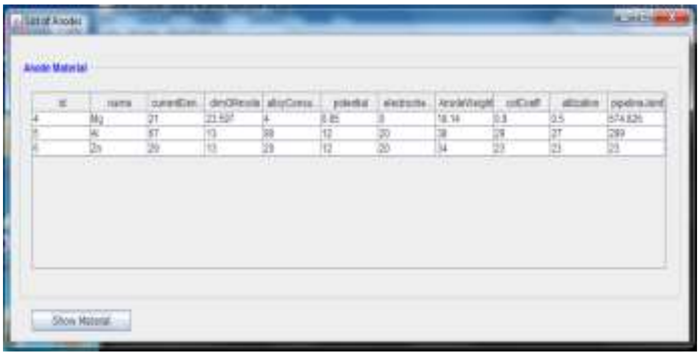


Figure 4.9: Anode parameters shown in tabular database form

Figure 4.10: Inputted anode properties before analysis showing mode of analysis

After input of the anode parameters, the type of anode (Mg, Zn or Al) is selected and the operational mode is selected i.e. single or multiple, the following result of the analysis leads to figure 4.11.

Figure 4.11: Output (Result) of anode Analysis showing operation mode (single or multiple)

After the operation mentioned above is done, the result which is some of the vital cathodic protection criteria for sacrificial anode such as required Current, Number of anodes required, number of anodes for systems life expectancy is shown:

## V. DISCUSSION

Substantial work has been done to make the technology of anode sizing more available and easier to access for the Oil and Gas industry. However, there are few software available to size anodes, some of which are online but not free. One of the processes used in sizing anodes is the use of a preprogrammed excel calculator sheet but it can only do sizing for one anode material. Apart from the excel calculator sheet, almost all the other software for the sizing of anodes are proprietary. This implies that the general public cannot have access to it free of charge.

In this work, we can do some comparison for two or more anodes, AL, Zn or Mg, based on their properties. Unlike other types of anode sizing tools that can only do sizing for one particular anode at a time, this software can size two different anodes at the same time and be able to produce a table for comparison.

The approach used in this work is slightly different from what others have done so far. This is because, it is a stand-alone software that can be shared on a class LAN network to support preliminary learning of anode sizing in Universities.

So technically speaking, it will, make anode sizing more accessible and create easier understanding in the exercise of anode sizing. The parameters so far done in this project as shown in Fig 5.11 shows output of anode parameters such as the required Current, Number of anodes required, number of anodes for systems life expectancy. What is done in this work is not absolute because, more anode sizing parameters can be added to make it more robust. Therefore, the software is scalable. More importantly, the figures gotten from the analysis, after approximation, relates correctly with the calculated data of a material with hand calculated approach.

## VI. CONCLUSION

This work is basically on the development of a software that can be used for sacrificial anode sizing for the cathodic protection of subsea structures. Agbami field offshore, off the coast of Niger delta of Nigeria is the location of interest. Data we have seen on issues that anodes have always been as a result of mistakes in the parameters put into consideration before sizing is done. Even though it will be difficult to get absolutely accurate sizing of anodes that can stand the entire service life of structure to be protected without retrofitting, software such as this could help in enormous ways to have sizing of nodes done for specific environments without much consideration of ranges in values. This is because, codes and standards have ranges of parameters for zones and environments.

Comparing the results gotten from the customized software used in estimating the number of anodes for the "Production Main Flowline Manifold Side End Fitting "and the available real life data shows that the software is accurate compared with the real field data.

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