# Sacrificial anode designing for the corrosion protection of underground pipelines using COMSOL Multiphysics

***A Thesis***

*Submitted in partial fulfillment of the*

*requirements for the award of degree*

*of*

**MASTER OF TECHNOLOGY**

*by*

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# CANDIDATE DECLARATION

I hereby certify that the work which is being presented in the thesis entitled "**Sacrificial anode designing for the protection of underground pipelines using COMSOL Multiphysics simulation**" in the partial fulfillment of the requirements for the award of the degree of **Master of Technology** and submitted in the **Department of Metallurgy Engineering and Materials Science, Indian Institute of Technology Indore** is genuine record of my work carried out during the time period from August 2021 to June 2022 under the supervision of Dr. Mrigendra Dubey (Associate Professor) in the Department of Metallurgy Engineering and Materials Science (MEMS), Indian Institute of Technology (IIT) Indore. I have not submitted the matter presented in this thesis for the award degree to another institute for any students.

31/05/22

**Signature of student with date**

**PIYUSH MEENA**

**------------------------------------------------------------------------------------------------------------------------**

This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

**Signature of the supervisor of** 01.05.2022

**M.Tech Thesis**

**DR. MRIGENDRA DUBEY**

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**PIYUSH MEENA** has successfully given his M.Tech Oral Examination held on **3 June 2022**

Signature of supervisor of M.Tech thesis. Convener,DPGC

Date:. 13.06.2022 Date: 14.06.2022

Signature of PSPC Member. Signature of PSPC Member

Date:. Date

# ACKNOWLEDGEMENT

It is my great pleasure to thank the people who made this project work possible. First and foremost, I would like to thank the IIT Indore faculty and staff for their commitment to educating their students.

I would like to thank my supervisor Dr. Mrigendra Dubey for believing in me to carry out this work under his supervision. His constant encouragement friendly interaction and valuable support have made this work to its present form.I would liketo thank my PSPC members Dr.Abhisekh Rajput and Dr. Sumanta Samal for their valuable time in looking and assessing my work during my mid-term and end-term presentation and for giving me valuable suggestions to boost my work progress.I am thankful to Dr. Vinod Kumar, Head of the department,MEMS for providing facilities that I needed throughout the M.Tech project work. I am also thankful to the faculty of this department for their constant valuable support and effort in teaching the concept to improve my knowledge in Materials science and engineering.Finally, I would like to thank my senior Yeeshu Kumar, Moupia Mukherjee, Chinthakuntla Mahender for their valuable suggestion in presentation and writing my thesis work. I thank my friends and my parents for their constant support.

# ABSTRACT

In this project work, we have created a underground pipeline structure model made of steel considering the pipeline burried in the soil environment and look over behaviour of corrosion inside the pipeline model by the help of COMSOL Multiphysics software. And the whole simulation is based on the basic principle of sacrificial anode Cathodic protection method. So we develop a sacrificial anode made of materials having high electrochemical potential so that the artificial anode is created the transfer of electron take place from sacrificial anode and protect our underground pipeline. This principle is basically the application of galvanic corrosion. The corrosion was explored by inspect the electrochemical parameters like electrolyte potential distribution and electrolyte current density distribution. Electrolyte potential distribution tells variation of electrolyte potential at that part of underground pipeline which is placed at a distance of 1 meter in front of sacrificial Anode. Electrolyte current density distribution shows that electrolyte current density value is maximum at that part which was infront of sacrificial anode made of materials like magnesium, aluminum, zinc, chromium and Zn-Cr alloy. The current density value which we got have been used to find corrosion penetration rate with the help of Faraday's law. This analysis shows that when we placed sacrificial anode made of magnesium which has high electrochemical potential then corrosion penetration rate is less in the pipeline as compared to other materials because transfer of electron is more in magnesium as compared to other anodic materials like aluminum, zinc .

# DEDICATION

*Dedicated to my guide*

*My lord Vishnu*

*My parents*

*My teachers*

*My seniors*

*My friends*

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# ACRONYMS

FDM - Finite difference method

FEM - Finite element method

BEM - Boundary element method

CP - Cathodic protection

SCC - Stress corrosion cracking

CBM - Coupled boundary method

# CHAPTER 1

# Introduction

### 1.1 Overview

In this research work, galvanic corrosion analysis of underground steel pipelines using computational method by COMSOL Multiphysics has been studied. Corrosion is identified as the main problem behind failure of oil and gas transport underground pipelines in soil and it also causes adverse impact on our environment.

### 1.2 Corrosion and its economic impact

Corrosion is a natural process in which the destruction or the wear of material occurs due to reaction with its environment. Corrosion is the process in which a metal transforms into a chemically more stable state such as oxide, hydroxide etc [1]. Metallic corrosion can be interpreted as a destructive and unintended attack of a metal . The metal is lost by deterioration called corrosion or by the formation of a metallic scale called as oxidation[1]. Most of the materials experience interaction with dissimilar environments often and these processes damage the usefulness of a material because of the reduction of its properties like mechanical (hardness or strength), physical properties or appearance of material. Corrosion is a detrimental factor that causes the deterioration and failure of engineering structures resulting in significant economic losses and even a potential threat to humanity [2].

Corrosion may have a negative impact on human health, the environment, and environmental security in ways that could not be easily quantifiable in terms of lost GDP. Apart from the economic losses it took sometime life also. Some major accidents due to corrosion such as the Aloha accident (1988), Bhopal accident (1984), Silver bridge failure (1997), Sinking of the Erika (1999) have been reported already. These accidents remind us of the severity of corrosion, and it cannot be ignored[2].

### 1.3 Electrochemical consideration of corrosion

Electrochemical degradation of metal occurs because of oxidation and reduction reactions in presence of acidic or basic environment. For metallic material corrosion behaviour is understood by certain reaction with its environments such as oxidation and reduction reaction [3].

### 1.3.1 Oxidation reaction

In this metal atom loose one or more electrons and becomes positively charged ions or in other words metal ion shifts to a higher valence state from lower state[3]. This is called oxidation reaction and the site at which it occurs is defined as anode and reaction is known as anodic reaction. Suppose there is metal M which goes oxidation then the generic formula for such reaction is as follows[3].

$$\mathbf{M} \rightarrow \mathbf{M^{n+}} + \mathbf{ne^{-}} \qquad \text{(eq 1)}$$

### 1.3.2 Reduction reaction

The electron generated from oxidation reaction i.e. From the reaction at anode is consumed in the chemical reaction known as reduction reaction and the place at which this reaction took place is known as cathode. The general chemical equation for reduction reaction is given below[3].

$$\boldsymbol{R^{n+}} + \mathbf{n}\boldsymbol{e^{-}} \rightarrow \boldsymbol{R} \qquad \text{(eq 2)}$$

### 1.4 Forms of corrosion

Metal corrosion can be categorized into various different types of corrosion which is explained in detail below:

### 1.4.1 Uniform corrosion

Uniform corrosion is most common type of electrochemical corrosion which happens with the equal intensity over the entirely uncover surface of the material and often leaves or deposit on the surface. In other words, in the microscopic sense, the exposed surface undergo oxidation and reduction reaction uniformly[1]. The main source of uniform corrosion in steels and other metals and alloys in the natural environment is oxygen. For example, rusting of steel plate in seawater[1].

Fig 1 - Uniform corrosion of pipe in seawater[47]

*https://www.researchgate.net/publication/293817799*

**1.4.2 Galvanic corrosion**

Galvanic corrosion is corrosion of two or more electrically connected metals in which the more active metal act as anode(negative) and corrodes, while the less active metal acts as cathode and protected or when two different metals or alloys with varying configuration are electrically connected and dipped in an electrolyte and galvanic corrosion occur[8].

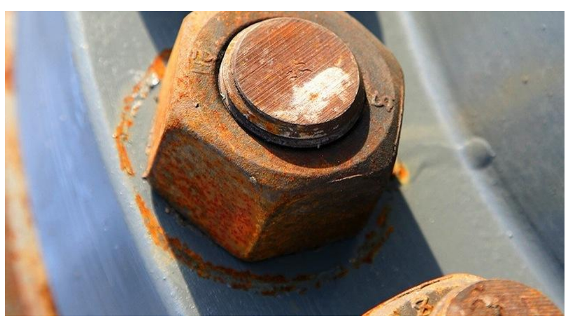

Fig 2 Galvanic corrosion diagram

*Source -Facility executive magazine*

### 1.4.3 Crevice corrosion

Crevice corrosion happens because of the uneven difference in concentration of ions in the electrolytic solution and between two regions of the same metal piece. For such type of concentration cell crevice corrosion occurs in the region that has lower concentration. Such resulting cells are also termed as concentration cells[8].

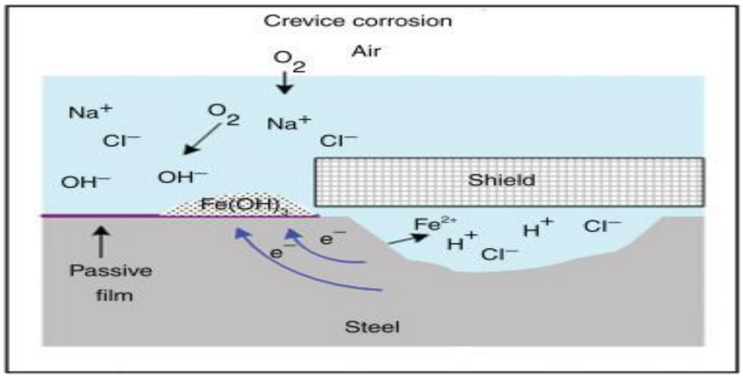


Fig 3 - Crevice corrosion diagram[47]

*Source - sciencedirect.com*

### 1.4.4 Pitting corrosion

Pitting is another type of localized corrosion in which there is the formation of little pits and holes as shown in figure 4 . It is forms of corrosion in which structures made of metallic materials failed catastrophically, often going undetected along with very little loss of metal until failure occurs. Stainless steel or the passivating material are more susceptible to this type of corrosion[1].

Fig 4 - Pitting corrosion occur on river bridge

### 1.4.5 Intergranular corrosion

As the name explains intergranular corrosion occurs preferentially occurs along grain boundaries for some alloys and in specific environments. We know that individual grains have different types of orientations and boundaries which is known as grain boundary. Generally, grain boundaries are not as reactive as that of grain itself but under some conditions grain boundaries are changed by impurities (Macroscopic disintegrates along its grain boundaries). Heat treatment and welding can alter the structure of metals which can contribute to intergranular corrosion. Intergranular corrosion can cause a significant reduction in mechanical properties and in serious situations can transform the metal into a pile of individual grains[8].

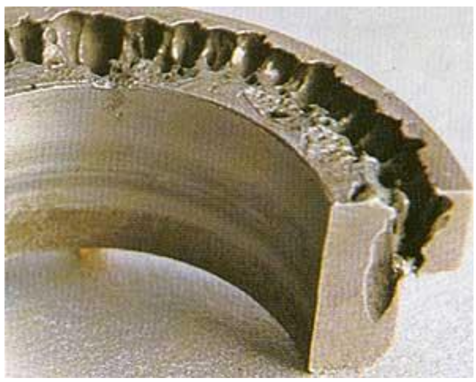

Fig 5 - Failure due to Intergranular corrosion

*Source - research gate.net*

### 1.4.6 Erosion corrosion

Erosion corrosion is a simultaneous action of chemical attack and mechanical action like abrasion by fluid motion[1]. Erosion-corrosion occurs because of the high velocity of electrolyte flow whose abrasive action enhances the corrosion. The initial stage involves the mechanical removal of a metal's protective film and then corrosion of bare metal by a flowing corrosive occurs. Usually erosion corrosion recognized by surface grooves and waves which contains contour that are the characteristics of the flow of flowing fluid. Various example encountered such as in piping, elbows, at bends and sudden abrupt changes in the cross-section of the pipe and when the pipe changes it flow direction. It is prevented by changing the design of the pipe and other components so that turbulence could be avoided.

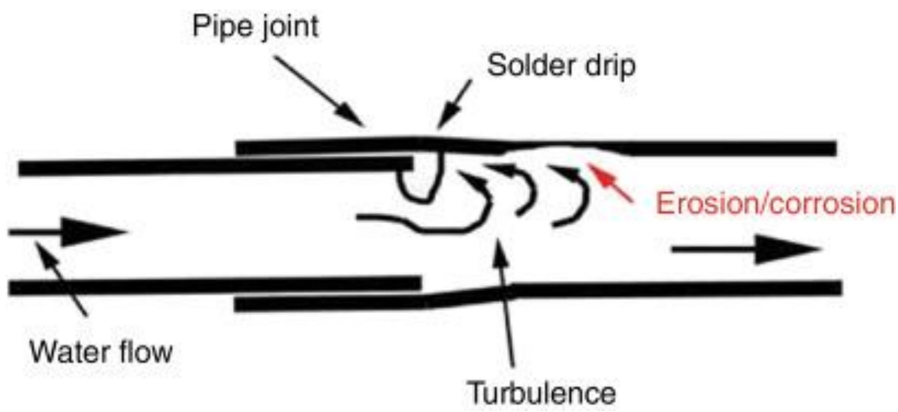


Fig 6 - Erosion corrosion diagram

*Source - researchgate.net*

**1.4.7 Stress corrosion**

This type of corrosion occurs by the combined action of applied tensile load/stress and corrosive environment. In most of cases such material that exist in a relatively inert environment becomes vulnerable to stress corrosion on the application of load.
Examples of stress corrosion cracking (SCC) are brass and stainless steel alloys. Brass alloy will crack in an ammonia rich environment when a minimum threshold applies load/stress is reached. The complex interactions of factors that trigger stress corrosion cracking are poorly known. However, it is understood that the chemical action (corrosion) causes surface irregularity or discontinuity and this acts as stress concentrator. The crack propagates due to the presence of a minimum threshold tensile stress combined with corrosion.

Fig 7 - Stress corrosion diagram

### 1.4.8 Selective leaching

In solid solution alloys selective leaching happens as one part or constituent is preferentially removed because of the corrosion process. For example, Brass is an alloy of Cu and Zn in a solid solution, Zn is selectively removed from the solid solution alloy and this process is called dezincification of brass. This phenomenon makes the brass porous and hampers its mechanical properties. It is advisable to add a small amount **of** Sn to the alloy to prevent dealloying. It is observed in brass when the natural colour yellow of brass turns into a reddish appearance.

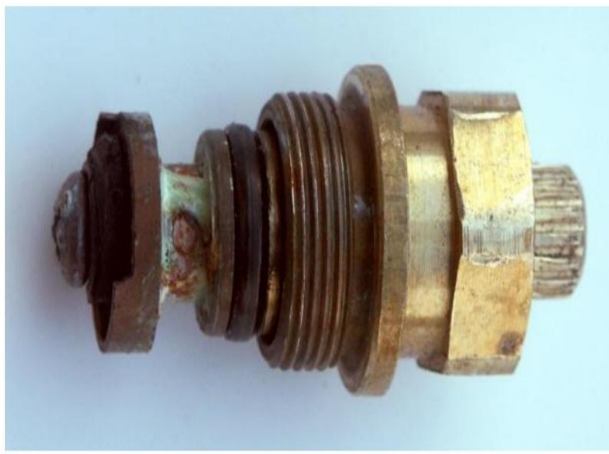

Fig 8 - Diagram of selective leaching

*Source - sciencedirect.com*

# CHAPTER 2 Literature review

## 2.1 Understanding corrosion in underground metal pipelines: basic principles

A substance or its qualities deteriorate as a result of a response with its surroundings. If a material is subjected to an environment in which material tendency to decay, it can corrode. These metal pipelines particularly those made of steel are subjected to a variety of corrosive conditions both within and externally. Of all the metals used in pipelines, iron-based metals are the most common. Iron is alloyed with a number of other metals to create steel structure that may shaped into pipe of various diameters, lengths. This pipe is joined (typically by weld) and buried to convey diverse products a few metres or across country to their final destination. Oil, natural gas, refined goods and a range of other liquids, gases, and slurries are examples of these products. These pipelines could be anywhere from a metres to over a thousand kilometres long. The pipe's diameter varies depending on the product and volume although it can range from a few centimetres to over a metre. The diameter of large water pipelines might be several metres. The thickness of the walls depending on the type of product and the pressure required[11].

Galvanic corrosion is a type of corrosion that occurs on metal pipelines. This helps us understand what happens during the rusting process. There must be an electrical (electronic transfer) and a chemical component present at the same time in order for comparable reactions to occur[4]. Four components are appeared at the same time for electrochemical corrosion to occur. These are:

*Anode* :The region of the structure where conventional current (CC) exits the metal and enters an electrolyte is referred to as the anode. Corrosion occurs where the CC separates from the metal.

*Cathode* :The section of the structure where CC reenters the metal from the electrolyte is called the cathode. The CC reenters the metal at the cathode contact ,where it is protected.

*Electrolyte* : An electrolyte is a medium containing ion that is electrically conducting through the movement of ions.

*External Path* : Path made between negative charge and positive charge.

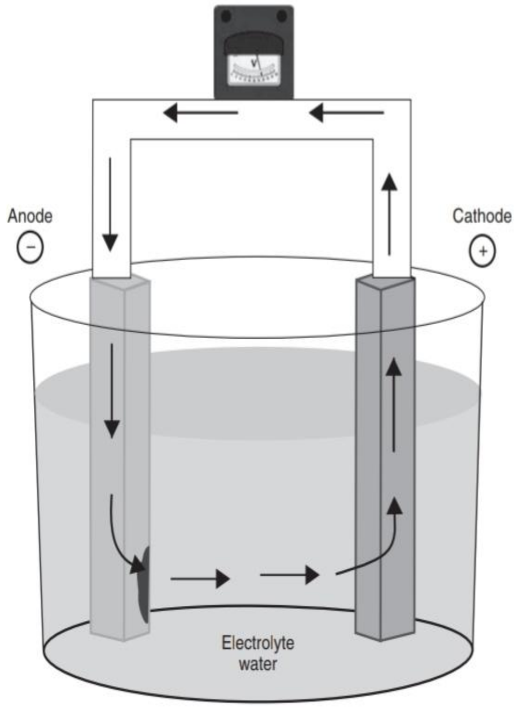


Fig 9 Basic corrosion cell[14]

**2.2 Assessing the significance of corrosion in underground pipelines**

Currently Oil, gas meet 54 percent of the world's energy demands and proven and recoverable oil and gas reserves last for more than 50 years. Pipelines are mostly used to carry these energy kinds. As a result, the world's high-pressure oil and gas pipelines total about 3500000 kilometres. The majority of these pipes were built many years before and they began their lives in pristine condition with external coating and cathodic protection to keep them from corroding (CP). However, as the pipeline ages the covering may deteriorate allowing corrosion to begin. As these pipelines are readied for the next 50 years of service, their ageing and the challenges it entails may limit their future use.

Pipelines are a very safe mode of transportation with an excellent safety record yet corrosion is a major cause of pipeline failure on both onshore (underground) and offshore pipelines. Over a 20 year period (1993–2012), data from the United States 500-mile (800-km) network of onshore hazardous (e.g., petroleum and petroleum products)liquid pipelines and natural gas pipelines demonstrates that.


Fig 10. Transmission pipeline [25]

**2.3 Detection of corrosion**

Common methods of detection of corrosion are as follows:

● Excavation

● Ground survey

● internal inspection using inline tools

Usually, the most common means of identifying and quantifying corrosion is pipeline excavation but it is also the most expensive technique. It's usually only employed as a last resort because it may need pressure decrease which has operating costs. Monitoring CP and coating condition from above ground can be utilised to infer the existence of corrosion. The following are some examples of inspection techniques:

| Type of survey | Survey technique | Type of survey |
|---|---|---|
| Soil survey | Soil resistivity.<br>Soil chemical analysis. | Soil survey |
| Coating survey | Pearson.<br>Signal attenuation (Cscan).<br>Current mapper.<br>DCVG (can also indicate CP status). | Coating survey |
| CP survey | CP monitoring data e.g., off potentials.<br>Close interval potential (can also indicate coating status). | CP survey |

**Table 1- ground CP surveys for underground pipelines**

We can also use technologies that move with the product flow to check and monitor our pipelines internally. Pigs or in-line inspection vehicles are the name for these tools

### 2.4 Protection of underground pipeline by using Cathodic protection method

Corrosion can be prevented and controlled in a variety of ways. The cathodic protection is one of them . Cathodic protection is a corrosion control technique that involves making a metal surface the cathode of an electrochemical cell. The metal to be protected is connected to a more readily corroded "sacrificial metal" that serves as the anode in a simple technique of protection. Instead of the shielded metal, the sacrificial metal corrodes. An external DC electrical power source is utilised to supply sufficient current for structures such as long pipes where passive galvanic cathodic protection is insufficient[33].

#### 2.4.1 Cathodic Protection (CP) and Its Method of Operation

Cathodic protection systems can be complex in design but their operation is based on the bimetallic or galvanic corrosion principle discussed previously. We may purposefully couple metals together to ensure that one cathodically protects the other by understanding the fundamentals of this form of corrosion. To put it another way, if we wish to protect a certain metallic structure we can establish conditions in which that metal serves as the cathode of an electrochemical cell. We can assure that the anode sacrifices itself by corroding preferentially over its cathodi ccounterpart by electrically connecting the metal to be protected to a more anodic (electronegative) metal.

Cathodic protection systems are used in a variety of sectors to protect a variety of structures in difficult or hostile conditions. Cathodic protection systems are used in the oil transport industry to prevent corrosion in fuel pipelines, steel storage tanks.This protection technology is also utilised on steel piles and ship hulls in the marine industry. Galvanizing is another method of cathodic protection that is often used to safeguard steel members and steel structures.

### 2.4.2 Types of Cathodic protection method

1. Sacrificial anode Cathodic protection method - The sacrificial anode is connected directly or indirectly to the metal be protected in passive cathodic protection systems. The difference in potential between the two different metals provides enough power to form an electrochemical cell which drives galvanic or bimetallic corrosion[25]. The structural steel elements of offshore rigs and platforms are often protected with this type of protection in this industry. To serve as the sacrificial metal aluminium bars are put directly on steel sections. A similar approach is used to cathodically preserve steel heater etc[25].

2. Impressed Cathodic protection method - Passive cathodic protection solutions may not be practicable in large structures. The quantity of sacrificial anodes required to offer effective protection can be either idealistic or unworkable. An external power source is employed to aid in driving the electrochemical processes in order to resolve this. Impressed current cathodic protection is the name for this method (ICCP)[25]. Long structures such as subterranean pipelines are appropriate for ICCP systems. For ICCP protection, the flanges of joining pipes are frequently insulated using isolation kits to break the pipes into smaller and more manageable parts.

## 2.5 Literature review on Cathodic protection modelling

The purpose of determining the relevant parameters of the cathodic protection system parameters, mathematical models based on calculation of electrical potential distribution and current density on the surfaces of electrode which are used.

**2.5.1 Finite difference method (FDM) -** In the early seventies of the last century, the finite different method was used to solve the problem of the distribution of electrical potential and the current density of the cathodic protection system . This process requires discretization of the entire domain of interest with a network[27]. Solutions are located in network nodes.

Although by using this method results with satisfactory accuracy are obtained, it is very rarely used when modelling realistic cathodic protection systems because of the need for discretization of the entire domain. The disadvantages that have eliminated this method from this field are long time needed for calculations especially in the case of complex underground structures that need to be modelled in 3D space. Long time needed for calculation is caused by a large number of nodes required for calculation[27].

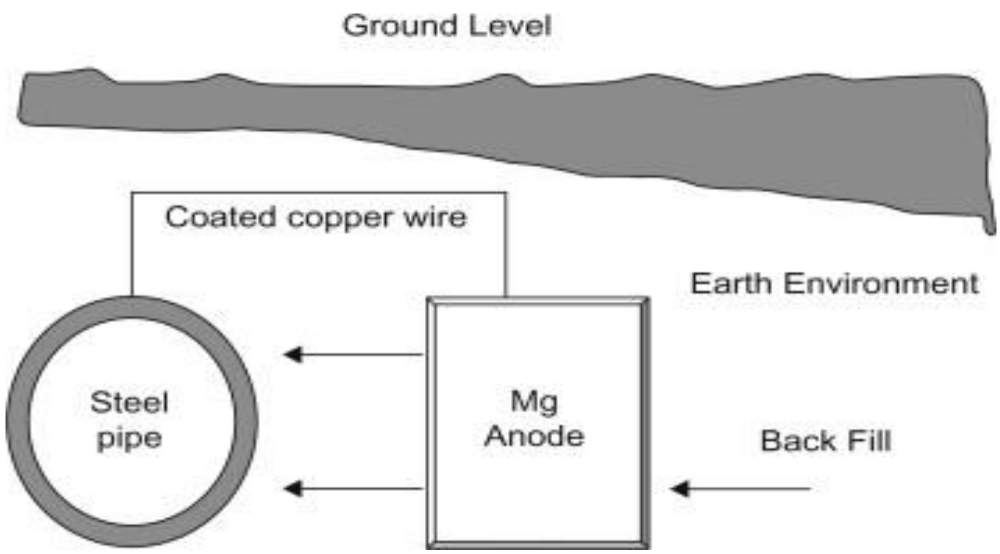


Fig 11 Sacrificial anode protection method[25]

**2.5.2 Finite element method (FEM) -** The FEM is one of the most frequently used numerical methods in science and engineering. It is characterized by robustness, modularity and multidisciplinary. In the finite element method, the entire domain of interest is classified into the volumetric elements of the finite dimensions. For each finite element, a set of algebraic equations is written by solving those yields the distribution of fields within each finite element. Unlike the FDM the FEM is algorithmic and relatively simple to program for general equations of electromagnetic fields. As with the modelling of most engineering problems, the finite element method has been found to be applied in the field of cathodic protection systems.

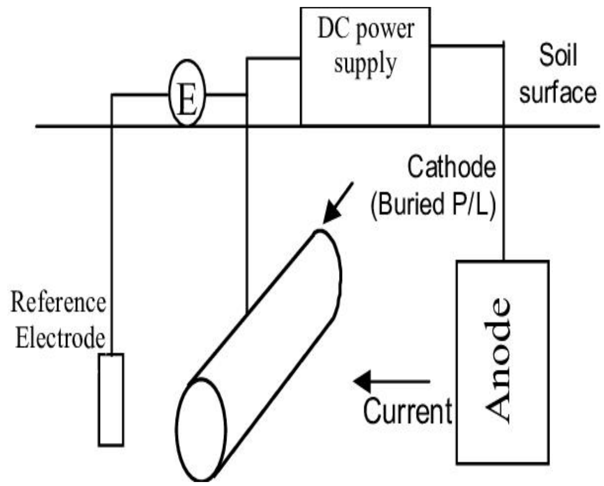


Fig 12 - Impressed current Cathodic protection method[25]

However, this method has one disadvantage when modelling the cathodic protection system of underground pipelines due to the need for discretization of the entire domain (electrolyte) considered as a semi-infinite domain and due to a large difference in the subdomain dimensions (electrolyte as a semi-infinite subdomain and for example, the pipeline wall thickness). This results in a large number of finite elements and therefore a large number of algebraic equations and consequently requires a long time for calculation.

**2.5.3 Boundary element method (BEM) -** One of the most efficient methods for solving issues in the field of application of cathodic protection systems is the boundary element method (BEM). The basic benefit of this method is that discretization is required only at the boundary of the domain of interest and there is no requirement for discretization of infinite boundaries. For the modelling of the cathodic protection system of underground or underwater metallic installations using the boundary element method. Laplace's partial differential equation (LPD) which is valid for the considered domain (electrolyte) is transformed into the integral field equation that only treats the boundary surfaces [33]. The discretization of this equation as well as the application of boundary conditions leads to the formation of the system of algebraic equations that need to be solved. For non-linear boundary conditions, such as the case of cathodic protection system modelling the system of equations is nonlinear and it is important to use iterative methods like the Newton - Raphson method .As the most suitable process for calculating the parameters of the cathodic protection system of underground metallic installations this method has been improved during the last three decades through hybridization with other mathematical methods. As such, it has been used for specific calculations in the application of the CP system.

**2.5.4 Coupled boundary method-** Although the boundary element method is the most frequently used methods , it does not give satisfactory results in the case of very long electrode surfaces such as long underground pipelines protected by a cathodic protection system. The reason for this lies in the fact that this method treats the electrode systems as equipotential i.e. does not take into account the potential drop occur due to the resistance of the material from which the electrodes are made. To overcome this problem hybrid boundary element/finite element method is proposed in literature . The boundary element method is suitable for solving stationary current field problem in infinite and semi-subsurface domains  so it is suitable for calculating electric potential. On the other side, the finite element method is suitable for solving stationary current field of bounded domains, therefore it can be applied for the field calculation within the electrodes. The potential difference on the electrode/electrolyte interface is calculated using the hybrid boundary element/finite element method.

# CHAPTER 3

# Simulation work

### 3.1 Objective

The oil and gas industry has a number of obstacles in terms of pipeline operation, and it is pressurized  to meet demand to work in a harsh and hostile environment in order to transport oil and gas from one location to another. Corrosion is a regular occurrence in such pipelines since they are exposed to an extremely corrosive condition. By COMSOL Multiphysics software, we constructed a 3D model to explore the corrosion of oil and gas pipelines exposed in a soil corrosive environment, taking into account the experimental limitations. We used steel as the pipeline material and an electrolyte medium (soil) with a 20 S/m electrical conductivity for this study.

In this project work, we examined the variation of electrolyte current density and electrolyte potential on a underground pipeline burried under the soil and we placed a sacrificial anode at a distance of 1 meter from pipeline. The entire investigation is centred on the use of a sacrificial anode. This method is a sort of cathodic protection in which a less noble material functions as a sacrificial anode and is connected to the structure to be protected by metallic conductors. Magnesium, aluminium, and zinc are the materials used for this. They both provide and consume electrons for the structure to be protected. The naturally occurring electrochemical potentials of various metals are utilised in SACP applications to provide protection. Sacrificial anodes do not require external electricity; instead, they generate their own power and require minimal maintenance.

### 3.2 Computational model

3-D model of the under burried pipeline was created having cylinder shape with dimensions 20 m in lenght and 1 meter in radius and a sacrificial anode was developed of cylindrical shape which is placed 1 meter from pipeline having dimensions 1 m in lenght and 0.5 m in radius were created by the help of COMSOL Multiphysics version 5.5 with a single electrolyte having electrical conductivity 20 S/m and  steel as underground pipeline material and high electrochemical potential material as a sacrificial anode material. Figure shows the developed pipeline model.

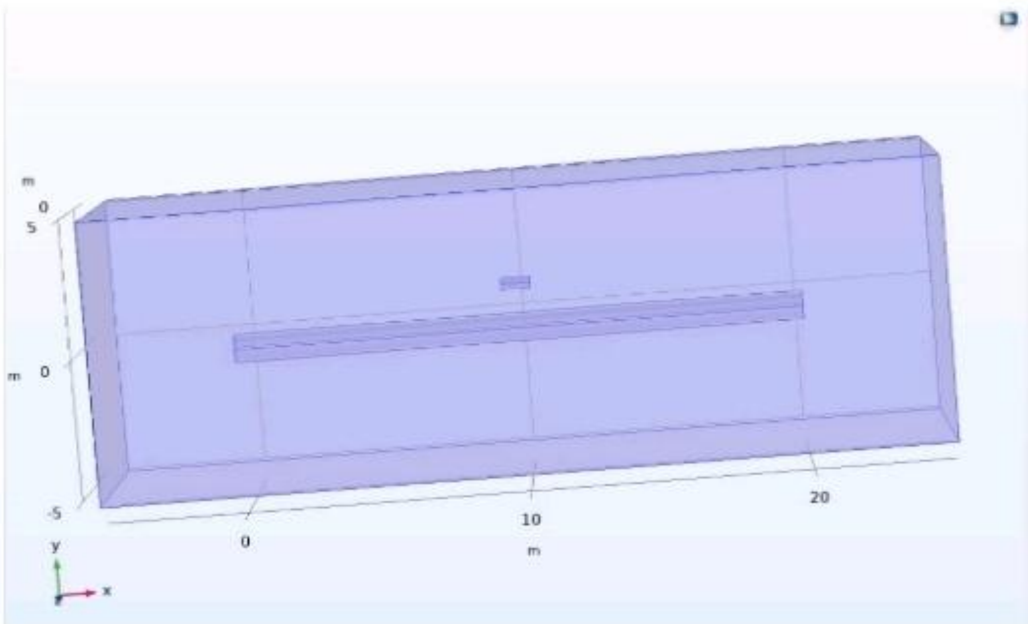


Fig 13 Geometrical representation of developed 3d Model

**3.3 Model parameter**

A hollow cylindrical shape pipeline is built by taking height 20 meter and radius 1 meter which is placed in a box like geometry filled with soil and this soil act as an electrolyte. Notably, the model was created with the real world problem of the oil and gas business in mind. This software allows the user to examine the model using main, secondary, and tertiary current distribution interfaces. For the constructed model, we have choose primary current distribution for the examination of Galvanic corrosion.

**3.4 Meshing**

For the produced 3-D model, a simple physics controlled mesh is employed with finer element sizes. The meshing of the model in front of the sacrificial anode is shown in Figure 2. The model is separated into non overlapping components known as elements as a result of meshing. The answer of each component is represented by an unknown function, and mathematical model is deduced via approximation and assembly of the component (element) set. As a result, discretization of the domain is required for finite element.

**Table 2 computational parameters for the inspection of Galvanic corrosion on a 3d pipeline model**

| Parameter | Value |
|---|---|
| Steel pipeline Height | 20 m |
| Steel pipeline radius | 0.5m |
| Sacrificial anode Height | 1m |
| Sacrificial anode radius | 0.2m |
| Soil resistivity (electrolyte) | 20 ohm meter |

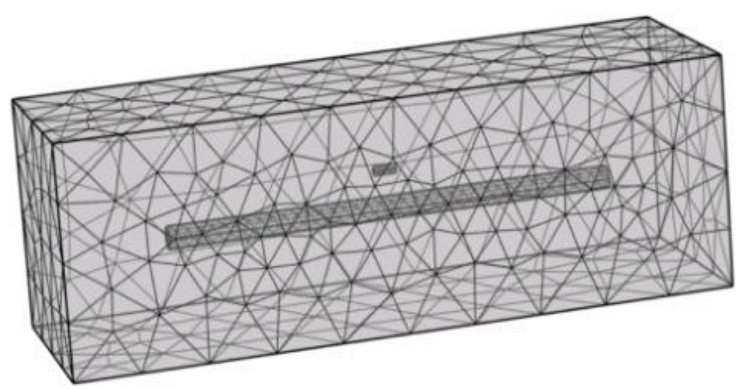

Fig 14 schematic representation of meshing

| Description | Value |
|---|---|
| Maximum element size | 15.4 |
| Minimum element size | 1.12 |
| Curvature factor | 0.4 |
| Resolution of narrow regions | 0.7 |
| Maximum element growth rate | 1.4 |
| Predefined size | Finer |

Table 3 Meshing unit for the development of model

**3.5 Governing Equation**

3.5.1 Primary current distribution

Equations -

$$\Delta \, . \, \mathbf{i_1} = \mathbf{Q_1} \, , \quad \mathbf{i_1} = -\sigma_1 \nabla \emptyset_1 \qquad \text{(eq 3)}$$

$$\nabla \, . \, \mathrm{i_s} = \mathrm{Q_S} \, , \; i_s = -\sigma_s \nabla \emptyset_s \qquad \text{(eq 4)}$$

$$\emptyset_1 = phil \, , \; \emptyset_s = phis. \qquad \text{(eq 5)}$$

3.5.2 Electrolyte 1

Equations -

$$\nabla \, . \, \mathrm{i_1} = \mathrm{Q_1} \, , \; \mathrm{i_1} =- \sigma_1 \nabla \emptyset_1 \qquad \text{(eq 6)}$$

3.5.3 Insulation 1

Equations-

$$-\mathrm{n} \, . \, i_1 = 0 \, , \; -\mathrm{n} \, . \, i_s = 0. \qquad \text{(eq 7)}$$

3.5.4 Electrode surface 1

Equations -

$$\emptyset_{s,ext} - \emptyset_1 = E_{eq} \quad \text{(eq 8)}$$

3.5.5 Electrolyte current density 1

Equations -

$$- n \,.\, i_1 = i_{n,1} \quad \text{(eq 9)}$$

### 3.6 Boundary condition

In the created 3-D model , sacrificial anode made of high electrochemical potential material act as a anode and underground pipeline as a cathode. Soil is considered as an electrolyte medium having electrical conductivity 20 S/m. There is no outside source of current in this whole model. The boundary condition at the primary and secondary current distribution interfaces is comparable to the insulation condition and may be stated using the following equation:

$$i_l \,.\, n = 0. \quad \text{(eq 10)}$$

### 3.7 Result and discussion

Two of the most essential electrochemical characteristics must be investigated in order to analyse corrosion in the pipeline using COMSOL Multiphysics software. The electrolyte potential is the first, and the electrolyte current density is the second. The potential generated by the ions in the electrolyte is referred to as electrolyte potential. Electrolyte current density which is proportional to the numberof ions transferred across the anode, is the current initiated by the movement of ions inside the electrolyte. For the constructed 3D model, it is most important parameters for calculating corrosion in the pipeline.

#### 3.7.1 Electrolyte potential distribution

The potential generated by the ions in the electrolyte inside the pipeline is known as electrolyte potential. Higher electrolyte potential values at any site imply that pipeline metal has a lower corrosion resistance. The distribution represented by using different colour and the corresponding electrolyte potential values are shown by the vertical scale shown below.

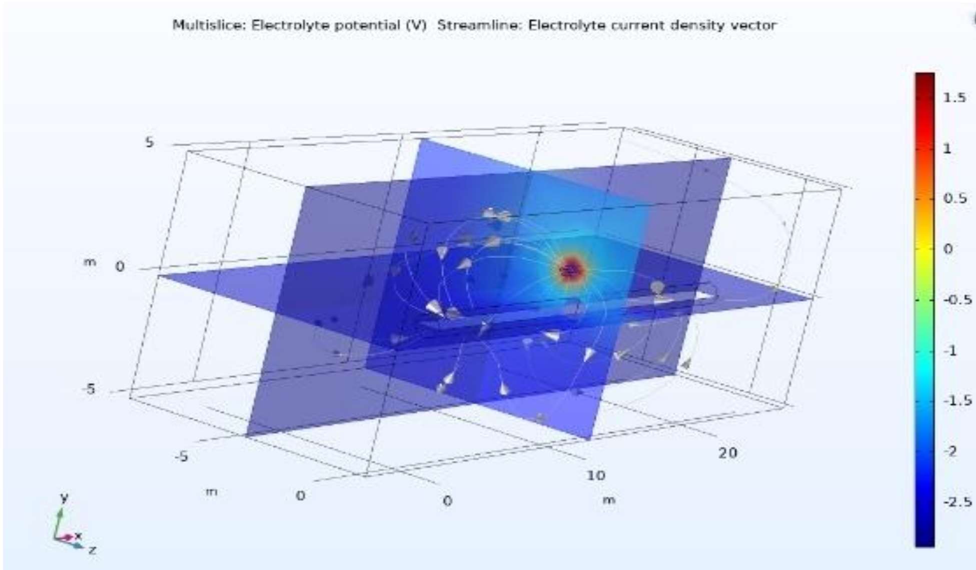


Fig 15 Electrolyte potential distribution when sacrificial anode is made up of magnesium

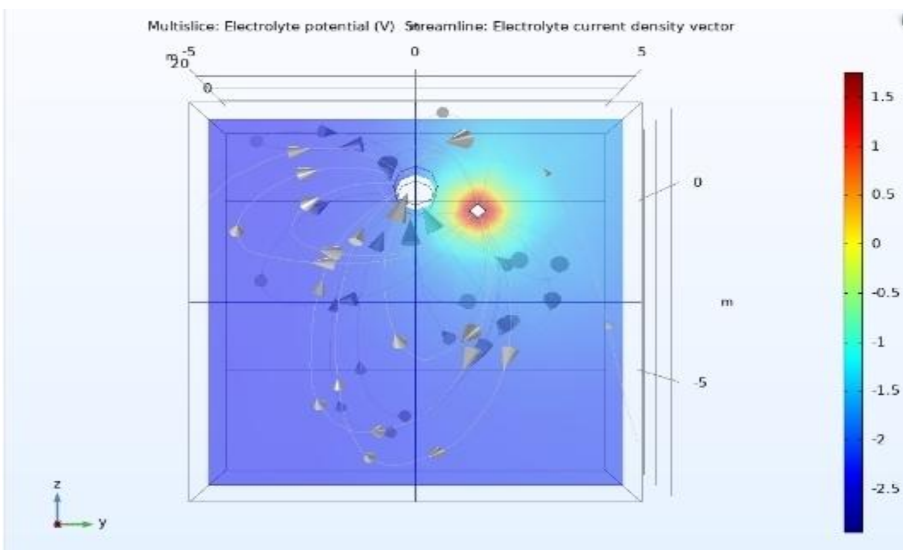


Fig 16 Electrolyte potential distribution in yz plane

### 3.7.2 Electrolyte current density

With the use of Faraday's law, it is another essential electrochemical parameter that is used to calculate corrosion rate. The rate of corrosion is directly proportional to the electrolyte current density. Figure depicts the distribution of electrolyte current density.

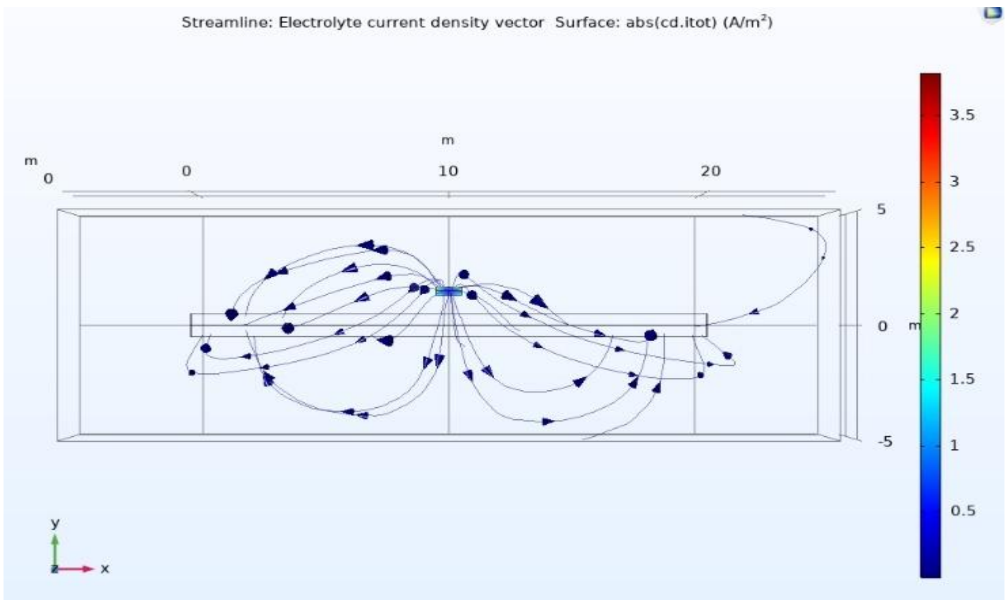


Fig 17 Electrolyte current distribution in xy plane

### 3.7.3 Three dimensional plot

In this figure it is clearly observed that part of metal pipeline which is in front of sacrificial anode have high potential and therefore rate of corrosion in that particular part is less as compared to other part of pipeline.

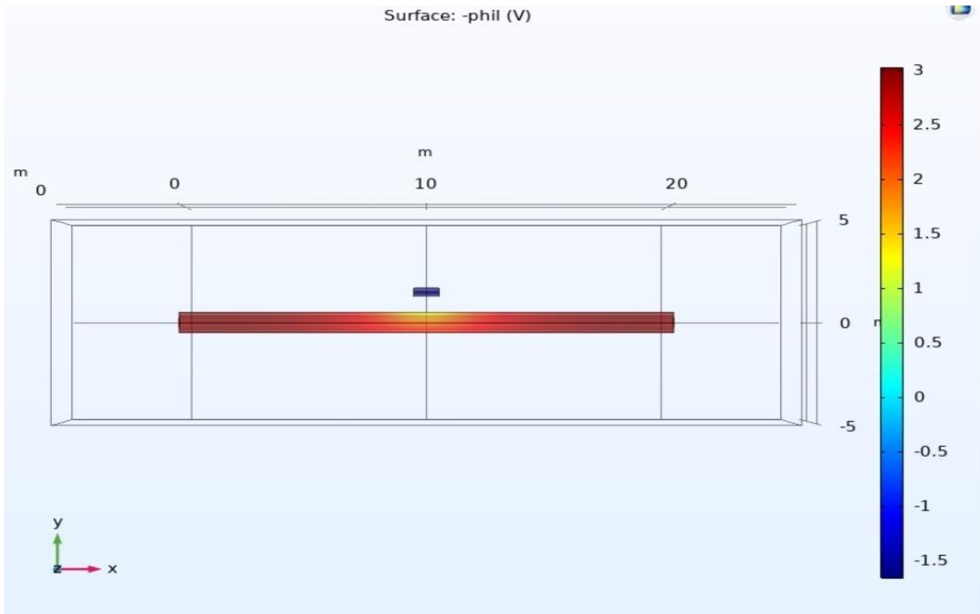


Fig 18 3d distribution of electrolyte potential

**Corrosion rate**

Corrosion rate is the rate at which any metallic component deteriorates in a given corrosive atmosphere.It can also be described as the amount of corrosion loss in thickness per year. The pace of deterioration is determined by environmental factors as well as the type and condition of the metal in question.

By the help of electrolyte current density vector at each point, the corrosion rate at each location may be calculated. The rate of corrosion can be calculated using Faraday's law using the following formula:

$$C_R = \frac{A_{eq}\ i}{\rho\ F} \qquad \text{(eq 11)}$$

Where C represents the current density in A/$m^2$, $A_{eq}$ represents the metal (Steel) weight in kg/equivalent, which is 0.02756 kg/equivalent, p represents the density which is 7870 kg/$m^3$ and F represents the Faraday's constant in C $mol^{-1}$, which is 96485.34 C $mol^{-1}$. The corrosion rate was calculated using the current density data obtained using Faraday's law.

**Table 4 Different obtained result when different sacrificial anode material is taken**

| Different sacrificial anode material | Potential drop (V) | Current density (A/m$^2$) | Corrosion rate (mm/year) |
|---|---|---|---|
| Magnesium | -0.75 | 0.0175 | $2.78\times10^{-6}$ |
| Aluminum | -1.66 | 0.0389 | $4.69\times10^{-6}$ |
| Zinc | -0.76 | 0.0178 | $2.83\times10^{-8}$ |
| Chromium | -0.74 | 0.0173 | $2.75\times10^{-9}$ |
| Zn-Cr alloy | -0.70 | 0.0164 | $2.607\times10^{-9}$ |

# CHAPTER 4

# SUMMARY

### 4.1 Conclusion

We successfully created a 3-D model of a steel pipeline and evaluated the rate of corrosion in a pipeline filled with electrolyte (soil) with a resistance of 20 ohm metre. With the help of COMSOL Multiphysics simulation, galvanic corrosion is investigated by looking at two parameters: electrolyte potential and electrolyte current density. From this analysis we conclude that sacrificial anode made up of higher electrochemical potential material reduces the rate of corrosion penetration. Finally, we were able to successfully evaluate corrosion behaviour inside the pipeline using the built 3D pipeline model. As a result, we anticipate that the modelling work described in this paper might be useful to analyse more actual problems related to galvanic corrosion thus facilitate cost effective and smart way for corrosion analysis.

### 4.2 Scope for future work

Among various computational method, COMSOL provides good result and computed prediction is in good agreement with experimental work. Thus, we strongly believed that this study definitely benefits other people who want to solve practical problem related to underground pipeline corrosion.

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