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PERFORMANCE ASSESSMENT SACRIFICIAL ANODE CATHODIC PROTECTION OF SUBSEA PIPELINE

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CERTIFICATION OF APPROVAL

Performance Assessment Of Sacrificial Anode Cathodic Protection Of Subsea Pipeline

By

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and the original work contained herein have not been undertaken or done by unspecified sources or persons.

MUHAMMAD FIKRI BIN OSMAN

CHAPTER 1:

ABSTRACT

The integrity of subsea pipeline depends mostly on the applied corrosion control. One of the corrosion control methods is using sacrificial anode cathodic protection, SACP. The performance of sacrificial anode cathodic protection is measured by the current supply and the operational life of the anode to protect the pipeline. In order to maintain the integrity of sacrificial anode cathodic protection, frequent inspection has been taken. However, there are no further assessment or analysis towards the performance of anode. The condition protection system only relies on the subjective data provide by the inspector. This study include aluminium and zinc as the sacrificial anode and carbon steel API 5L X65 as the cathode. The Objective of this study is to analyse on the corrosion rate of aluminium and zinc as well as to determine the most effective metal as a function of sacrificial anode metal. In this study, data are gathered from PETRONAS Carigali Sdn. Bhd. Peninsular Malaysia Operation, PCSB PMO. Two of their operating pipeline with different type of anode were selected and have been analysed on the corrosion rate of the sacrificial anode cathodic protection. Other than that, this study also includes data from laboratory simulation which are Linear Polarization Resistance test and weight loss test. As a reference, Det Norske Veritas, DNV RP B401 was used in order to design the sacrificial anode cathodic protection. Based on the results, it has been found that the corrosion rate of aluminium is higher than the other metals that are carbon steel API 5L X65 and zinc. To conclude this study, aluminium is found to be the most effective metal as sacrificial anode cathodic protection based on the corrosion rate, operational life and the current supplied by the metal.

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The author would also like to extend his thanks to all other lecturers that how their cooperation to the project. Not to mention, my gratitude towards the course mates in providing ideas and guidance on helping the project solutions involving software simulation and design application. Finally, the author wish to thank to those who has directly or indirectly involve in this project for their continuing supports and motivation during undertaking of this project.

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CHAPTER 2:

INTRODUCTION

2.1 Background of the Study

In oil and gas industries, one of the most crucial problems that company has to face is pipeline leakages. The main reason of pipeline leakages is corrosion either internal or external part of pipeline. However, there are several factors that can cause pipeline leakages such as dumping of heavy things like anchor under the sea. Companies have put much effort to overcome equipment failure due to corrosion. Though corrosion cannot be eliminated, it can be reduced. Corrosion inhibitor, oxygen scavenger, operational pigging and cathodic protection are the solutions of reducing rate of corrosion in the pipeline.

The application of cathodic protection has been widely used to protect the external part of pipeline. The installation of bracelet anodes has been done during coating of pipeline. Most of the pipelines are made from carbon steel metal for example, based on Det Norske Veritas RP-B401: Cathodic Protection Design (2005), types of carbon steel pipes are differentiated by the composition of the element in the pipe such as manganese, carbon, nickel, vanadium, zinc and ceramic. According to American Petroleum Institute 5L: Specification for Line Pipe (2004), the commonly used carbon steel pipes are X65, X52 and X60.

In order for cathodic protection to be effective to protect the pipeline, the metal used as the sacrificial anode must be more active than steel. Degree of active metal is defined through electronegativity series of metals. Metals that are highly active have the ability to easily loose electron when in contact with less active metals in certain environment which is the electrolyte. Most of operators preferred zinc as an anode however, when come to cost saving purpose, the preferable metal fall to aluminium.

Therefore, assessment of performance of sacrificial anode cathodic protection for subsea pipeline is needed in order to find the best metal as a corrosion control for carbon steel pipe.

2.2 Problem Statement

The integrity of pipeline is based only on the inspection both internal and external inspection. However, there are no specific assessment to check on the performance of sacrificial anode cathodic protection.

2.3 Objectives and Scope of Study

The objectives of the study are as follows:

1. To study the rate of corrosion of zinc and aluminium when in contact with carbon steel in seawater environment.
2. To study the effective metal as sacrificial anode cathodic protection for subsea pipeline.

Pipelines that used zinc and aluminium as anode bracelets are selected within PETRONAS Carigali Sdn. Bhd. Peninsular Malaysia Operation region. Data on corrosion rate of sacrificial anode (bracelet anode) are taken from Underwater Inspection Report by PETRONAS Carigali Sdn. Bhd. There are few codes and standard to be included such as Det Norske Veritas RP-B401: Cathodic Protection Design, PETRONAS Technical Standard 30.10.73.32: Design of Cathodic Protection Systems for Offshore Pipelines and PETRONAS Technical Standard 30.10.73.33: Installation and Commissioning of Cathodic Protection Systems. All the calculations involved are referred from the codes and standard as well as Installation of Anode Sled Report by Perunding Ranhill Worley Sdn. Bhd. Corrosion test, specifically electrolysis will be implemented to compare the findings between theoretical and experimental analysis.

CHAPTER 3:

LITERATURE REVIEW and/or THEORY

Generally, corrosion is a common phenomenon by which material deteriorates due to reaction with the environment. According to Theory of Corrosion and Cathodic Protection by J.B. Bushman (n.d), there are different terms used to describe the form or basic mechanism of corrosion. He preferred to use degradation of material when reacts with environment. On the other hand, based on ISO 8044, Corrosion of Metals and Alloys, corrosion is a physicochemical interaction between a metal and its environment which results in changes in properties of the metal. Thus, as the properties of metal changes, it will lead to impairment of the function of the metal. Corrosion is also said to be a destruction of a metal by chemical or electrochemical reaction with its environment (H. H. Uhlig, n.d.). In simple word, any material like wood, plastic, metal, polystyrene and rubber will experience corrosion. However, there are different terms to describe corrosion for each different material for example; rusting is used to describe corrosion for metal and tear is often used for rubber.

In addition, all metals are naturally found in corroded state which is the most stable state of metals. Other researcher claimed as an oxide state which is the state of iron ore. When metal is added with other composition of other elements to become another metals such as carbon, zinc, magnesium and silver, the metal will lose stability. However, as time goes by, metal will react with the environment and as the matter of that, it tends to go back to its original state. Corrosion process is occurs when metal change to oxide state as well as stable state. There are many forms of corrosion such as uniform, localize, pitting and galvanic corrosion.

Plus, in order for corrosion to occur, there are several components to be taking consideration. They are anode, cathode, electron path as well as ionic path. During the occurrence of corrosion, there will be anodic and cathodic reaction which represents oxidation and reduction process. As for the electron and ionic path, the terms value the condition of the environment where the electron or ion is transferred during corrosion process.

Corrosion has been a major problem in industries like manufacturing, construction, automotive as well as oil and gas. It is like a big threat for companies since corrosion might cause severe accident and would effect in losing an asset as well as customers and clients. In oil and gas industries, major threat of corrosion occurs at the equipment either in offshore or onshore. If the corroded equipment is feasible to be change or undergo maintenance like onshore or on offshore platform, it is not a problem. The most challenging threat which is a major crisis is when the equipment is either buried underground or located in the subsea. In this context, pipeline has to face this challenging threat since it is buried underground and installed in subsea.

Furthermore, based on Wikipedia (2013), pipeline is defined as a conduit made from pipe connected end to end for a long distance fluid or gas transport. In oil and gas industries, pipeline is a major transportation of gas and crude oil from platform to platform, platform to mobile storage which is the vessel and platform to onshore terminal. Pipeline are said to be the most economical transportation of product since it has an impressive safety record compared to other means of transportation such as through marine and railroad as well as trucking (PETRONAS Pipeline Training Module – Theory of Pipeline Design, 2012). According to PETRONAS Pipeline Training Module, the author stated that pipelines are non-disruptive means of land transportation since most of the pipelines are buried underground and located in subsea.

3.1 Galvanic Corrosion

According to Wikipedia on Galvanic Corrosion (2014), different metals have different electrode potentials, and when two or more are in contact in an electrolyte, one metal acts as anode and the other as cathode. The electro-potential difference between the dissimilar metals is the driving force for an accelerated corrosion attack on the anode member of the galvanic couple. The electrolyte provides a platform for ion migration whereby metallic ions move from the anode to the cathode within the metal. This leads to the metal at the anode corroding more quickly than it otherwise would and corrosion at the cathode being inhibited. The presence of an electrolyte and an electrical conducting path between the metals is essential for galvanic corrosion to occur.

The mechanism of galvanic corrosion has been widely used in many operations and manufacturing area of industries, purposely for protection of equipment, machines, pipes and structure and this method is called cathodic protection. There are two types of cathodic protection which is impressed current cathodic protection and sacrificial anode cathodic protection. The different between these two types of cathodic protection is the current supplied. Sacrificial anode cathodic protection mostly used for offshore structures and pipelines where the current supplied depends on the metal used for anode and cathode. On the contrary, impressed current cathodic protection includes a rectifier to control the amount of current supply and that is why impressed current cathodic protection widely used for onshore equipment since it is feasible to install the rectifier.

3.2 Key Parameters Affecting Corrosion for Subsea Pipeline

There are several factors that can affect external and internal part of subsea pipeline.

3.2.1 Frequency of Pipe Gauging or Cleaning.

Pipeline is used to transport crude oil and gas for a long distance in order to be stored in either vessel tank or terminal storage tank. As for crude oil pipeline, there will be much sludge accumulate in the pipe. The sludge might contain bacteria as well as sand and also seawater. These impurities carried along with the crude oil are harmful to the steel pipe since they are the catalyst for corrosion to occur. On the other hand, for gas transporting pipeline, one of the crucial maintenance aspect is to ensure zero amount of liquid hold up in the pipeline. Due to low temperature and pressure, gas tends to condense to fluid that might harmful to the pipeline. In order to avoid corrosion in the pipeline, there are methods implemented for gauging the pipeline as well as purposely for protection. Frequency of the gauging would affect the corrosion rate occur in the pipeline.

3.2.2 Metal Debris

Offshore platform commonly surrounded with other platforms and vessels. Vessels usually used for transport crude oil and gas as well as to carry equipment for offshore maintenance project. Metal debris is from the waste material or equipment from the maintenances such as scaffolding, electrode weld wire, metal tools and others. These materials somehow can be harmful to pipeline since it can create corrosion when in contact with the pipeline. Other than that, the anchor wire from the ship also will effect in the same situation as metal debris.

3.3 Development of the Technique on Cathodic Protection and Cathodic Prevention

The technique has been developed in the last 20 years in three phases. The first phase began in 1973 in North America, lasted approximately a decade and mainly concerned the protection of bridge deck contaminated by chlorides. In this years, new feeding and monitoring system like anode, overlays and electrodes were set up; furthermore protection and design criteria completely different from those utilized in cathodic protection in soil and sea water were proposed. However, above all, it was proved that cathodic protection in concrete could be a solution to reinforcement corrosion, especially in presence of high chloride levels where other traditional repair systems are inefficient or very expensive. At the end of this phase, there was a memorandum stated that the only rehabilitation technique that has proven to stop corrosion in salt contaminated bridge decks regardless of chloride content of the concrete is cathodic protection.

The 80s phase saw the introduction of the method outside North America and the development of new meshed anodes based at first on conductive polymeric materials and then on much more reliable mixed metal oxide activated titanium and on carbon containing paints. In addition, cathodic protection application was extended to the protection of bridge slabs and piles, marine constructions, industrial plants, garages and building affected by chloride corrosion. In this stage, cathodic protection developed a track record of success and reliability if properly designed and applied as well as showing significant capital cost savings compared with the extensive removal of chloride contaminated concrete and replacement or reconstruction approach.

Last phase sees the application of cathodic protection not only to control corrosion rate of chloride contaminated constructions but also to improve the corrosion resistance of the reinforcement in new structures expected to become contaminated. This type of cathodic protection named cathodic prevention, even if it utilizes the same hardware as the traditional cathodic protection in concrete, has different aims, features, operating conditions, effects and side effects. In particular, it has different consequences as far as hydrogen revolution in concerned and this make it even possible to apply it to prestressed structures without risk of embrittlement.

Indicatively until now cathodic protection has been applied to about large number of corroding reinforced concrete structures, and cathodic prevention to about half of it of new and almost all prestressed structure. The principles of cathodic protection in concrete are often erroneously considered as if they were just the same as those of cathodic protection in soil. To understand how cathodic protection in concrete works which is both cathodic protection to reduce or to stop corrosion and cathodic protection to prevent it, it is convenient to give few general considerations and definitions on corrosion and protection of metals with particular attention to steel in concrete and to resume the effect produced by the circulation of a current between an anode and a cathode through an electrolyte.

CHAPTER 4:

METHODOLOGY

4.1 Project Flow

Figure 1 below shows the flow of this project. There are three stages of data gathering run simultaneously in completing this project; data from design data which is from the standard (DNV-RP-B401), data from PETRONAS Carigali Sdn Bhd and data from experiment or corrosion test which includes Linear Polarization Resistance (LPR).

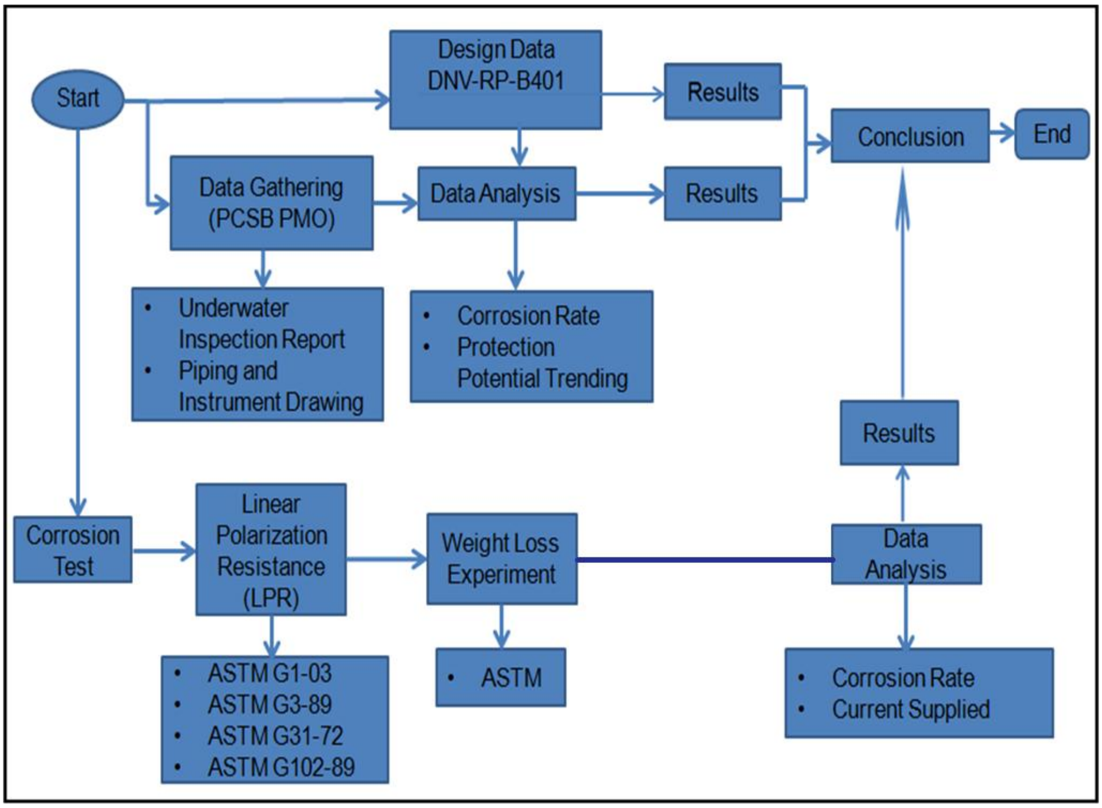


Figure 1. Flowchart of the Project

4.2 Test Parameters for LPR

In order to conduct LPR test, there must be some compulsory parameters that mimicking the original condition of reservoir. Table below show, the test matrix required to accomplish the LPR test.

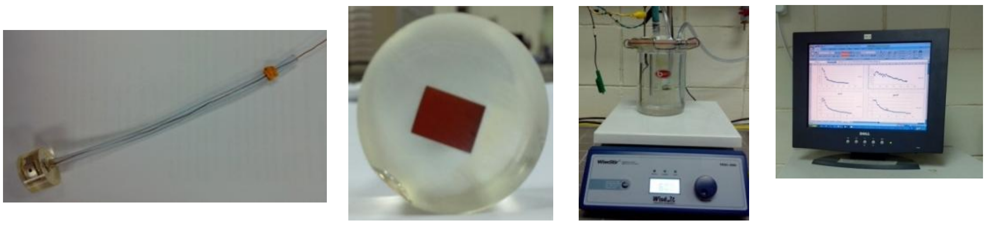
Table 1: Test Matrix

Test Matrix	
Standard(s)	• ASTM G1 • ASTM G3 • ASTM G31 • ASTM 102
Temperature (^oC)	25
Pressure (bar)	1
Material	Carbon Steel API 5L X65 Aluminium Zinc
Exposure Time (Hours)	24
pH	4
Tools	• Linear Polarization Resistance (LPR)

4.2.1 Test Setup

The main test to this project by using Linear Polarization Resistance (LPR) and below are the roughly step to accomplish the procedure as well as to get the corrosion rate (CR).

Table 2: Test setup and activity

No.	Activity	References	Description
1	Preparation of brine	ASTM D1141, Standard of procedure (SOP) and MSDS Surfactant	Synthetic Water • Softten Seawater, SSW  Figure 2: 3.0% NaCl
2	Selection of materials	API	Materials used as specimens for corrosion test: • API 5L – X 65 (Pipeline)
3	Grinding and polishing of specimen	ASTM G01	To make sure the surface of specimen free from impurities and any scratch  Figure 3: Grinding process
4	Linear Polarization Resistance (LPR)	ASTM G3	Apparatus of LPR as shown below:
	 Figure 4 a) Ribbon electrode; b) Specimen mounted into low viscosity epoxy; c) LPR test and d) LPR software program		

4.2.2 Procedure of Linear Polarization Resistance (LPR) method

Sample preparation

1) The specimens were cut into rectangular shape with dimension 1cm by 1cm and undergo grinding process using emery papers that have different size (Refer ASTM G31).

2) The orientation of specimens must be synchronize and frequently when conducting the grind and polishing process. The scratches from the previous need to remove before progressing the finer grit.

3) The specimens were rinsed with deionized water and acetone and then placed in proper medium to avoid air from contact the clean surface.

Solution preparation/electrolytes

1) The brine was prepared by adding Sodium Chloride (NaCl) only.
2) 1 liter of 3.3% of NaCl was used in LPR test and the calculation can be shown below:

Equation 1: Preparation of SSW

$$\text{3.0\% NaCl brine:}$$
$$3.0\% \rightarrow 30{,}000\text{mg/l}$$
$$= \frac{30{,}000\text{ mg}}{1\text{l}} \times 1\text{l}$$
$$= 30{,}000\text{ mg}$$
$$= \mathbf{30\ g} \ldots \text{of } \mathbf{NaCl} \text{ and dilute with } \mathbf{970g\ of\ distilled\ water}$$

Electrode preparation (Ribbon electrode)

1) The pre-prep specimen was mounted into the low viscosity epoxy resin (Figure 12a) and the exposed area was measured carefully.
2) Before mounting, the electric contact was made to the back surface of specimen by attaching a thin copper wire using solder.

LPR Test

1) The apparatus were setup according to ASTM G3 and ASTM G31.
2) Prepared brine solution was measured 900ml and pour into the 1 liter beaker (Figure 12c
3) Purging process was conducted by inserting CO_2 gas into the brine until reaching the desired pH value.
4) The clamp was used to tight the beaker so that no gas came out when running the test.
5) There were three probe using throughout the test which were ribbon electrode, auxiliary probe and references probe.
6) The ribbon electrode was immersed into the brine solution and the temperature and pressure was setup accordingly. The reaction was more effective when the position of ribbon electrode was lower and near to references probe.
7) The LPR test was using direct current (DC) and connected with the software program (Figure 12d).
8) The test was monitored every hour and continuously running according to test matrix.

4.3 Weight Loss Test

4.3.1 Sample Preparation

1) Firstly, grind the specimens using abrasive paper until grid 600.
2) Rinse the specimens thoroughly with deionized water and lastly with alcohol.
3) then blow the specimens using air blower or inert gas.
4) the test specimens shall be handled with gloves and tweezers to avoid contamination of the surface after cleaning.
5) the clean, dry specimen should be measured and weighed. Dimension determined to the third significant figure and mass determined to the fifth significant figure are suggested.
6) Prepare 3% test solution by mixing 30 gram sodium chloride with 100 mL distilled water.
7) Stir the mixture until it dissolve properly.
8) Hang the specimen using nylon string inside the test solution.
9) Record the starting time.

4.4 Key Milestone

Table s below show the planning of project for Final Year Project 1 and Final Year Project 2.

Table 3: Key Milestone for Final Year Project 1

Final Year Project 1															
No.	Details / Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection of Project Topic														
2	Preliminary Research Work														
3	First Draft of Extended Proposal														
4	Submission of Extended Proposal														
5	First Draft of Proposal Defence Presentation														
6	Proposal Defence														
7	First Draft of Interim Report														
8	Submission of Interim Report														

Table 4: Key Milestone for Final Year Project 2

Final Year Project 2															
No.		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Data Gathering and Analysis														
2	Set Up Experiments														
3	Data Analysis & Calculation														
4	First Draft of Final Report														
5	Final Report Submission														
6	Technical Presentation (VIVA)														
7	Final Report Submission (HARDBOUND)														

4.5 Gantt Chart

Table 5 below shows the project activities throughout two semester.

Table 5: Gantt Chart

No.	Details / Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14
								Final Year Project 1							
1	Selection of Project Topic														
2	Preliminary Research Work														
3	Extended Proposal														
	First Draft														
	Submission of Extended Proposal														
4	Proposal Defence														
	First Draft of Presentation Slides														
	Presentation														
5	Interim Report														
	First Draft of Interim Report														
	Submission of Interim Report														
								Final Year Project 2							
7	Data Gathering and Analysis														
	Underwater Inspection Report														
	Piping and Instrument Diagram														
	Findings														
	Analysis of the Findings														
8	Experiments														
	Test on sample 1 and 2														
	Findings, Data Analysis and Calculation														
9	Final Report														
	First Draft of Final Report														
	Final Report Submission														
10	Technical Presentation (VIVA)														
	First Draft of Presentation Slides														
	Mock Up Presentation														
	Final Presentation														
11	Final Report Submission (HARDBOUND)														

CHAPTER 5:

RESULTS AND DISCUSSION

According to Figure 1: Flowchart of the Project, this study comprise of four stages of data collection and data analysis. There are two experiments conducted which is weight loss and Linear Polarization Resistance (LPR). These experiments are to determine the corrosion rate of selected metals which are carbon steel API 5L X65, aluminium and zinc. Other than that, there are also theoretical data analysis to calculate corrosion rate of the sacrificial anode cathodic protection (SACP). Det Norske Veritas, DNV RP-B401 is used as reference in designing the anode bracelet as well as anode bar. Most of the data used in designing anode bracelet and anode bar such as details of pipelines and sacrificial anodes are collected from PETRONAS Carigali Sdn. Bhd. Peninsular Malaysia Operation, PCSB PMO.

5.1 Underwater Inspection Data and Findings

Underwater inspection is a time base activity done by the operator to look over the condition of their instrument such as pipeline, base of the platform, plem etc. In this context of study, data included by underwater inspection report is limited only to the inspection of pipeline that cover up the condition of anode bracelet or anode bar also known as retrofit anode. Remotely operated vehicle, ROV is used to view the pipeline and recoded data encompasses the condition of anodes, pipeline coating and other reported activities such as marine growth and waste debris from ship and platform.

According to the underwater inspection report by PETRONAS Carigali Sdn. Bhd. Peninsular Malaysia Operation, two pipelines are selected based on the different type of metal used as sacrificial anode cathodic protection. There are two information given by the ROV which are sacrificial anode protection potential and depletion rate of the sacrificial anode.

Protection potential is measured by voltmeter fitted to the ROV which is stabbed during the inspection. However, the depletion rate of sacrificial anode is subjectively report by the ROV pilot. There are no standards or guidelines practice by ROV pilot in verifying the rate of depletion of sacrificial anode.

Below are the details of the pipeline.

Table 6: Details of the PETRONAS Carigali Sdn Bhd Peninsular Malaysia Operation pipelines.

	PMOPL 1 - 8" Platform 1 to Platform 2 (4.4 km)	PMOPL 2 - 10" Platform 3 to Platform 4
Installation Year	1984	2003
Inspection Year	2001	2011
Anode Type	Zinc	Aluminium
Anode Weight	124 kg	155 kg

5.1.1 Corrosion Rate of Sacrificial Anode Cathodic Protection for PCSB PMO Pipeline

5.1.1.1Depletion Rate and Protection Potential of PMOPL 1 - 8" Platform 1 to Platform 2

Table 7 below shows the data provide from PCSB PMO on the details of performance of sacrificial anode cathodic protection. The provided data are based on protection potential and percentage of depletion. Depletion rate and the remaining life of the anode were analysed according to the percentage of depletion. Summary of the data are shown in Figure 5 and Table 8.

Table 7: PMOPL 1 - 8" Platform 1 to Platform 2 Sacrificial Anode Particular

Kilometer Post (km)	Protection Potential (mV)	Depletion (%)	DepletionRate (%/year)	Remaining Life (year)
0.001	-962			
0.001	-974			
0.001				

0.001	-950			
0.001	-974			
0.001	-961			
0.017	-974			
0.076				
0.205		50	2.941	17
0.325	-999	60	3.529	17
0.447	-990	50	2.941	17
0.576	-1001	50	2.941	17
0.694	-1012	50	2.941	17
0.927	-1014	75	4.412	5
1.060	-1006	75	4.412	5
1.181	-1005	50	2.941	17
1.294	-1008	50	2.941	17
1.414	-1004	50	2.941	17
1.551	-1010	50	2.941	17
1.671	-1002	75	4.412	5
1.791	-1011	50	2.941	17
1.912	-1000	50	2.941	17
2.037	-1011	50	2.941	17
2.160		50	2.941	17
2.530		50	2.941	17
2.876		60	3.529	17
3.012		50	2.941	17
3.251		50	2.941	17
3.628	-948	50	2.941	17
3.873	-1004	50	2.941	17
3.997	-1000	90	5.294	1
4.120	-1011	95	5.588	1
4.240		95	5.588	1
4.396	-961	100	5.882	0
4.396	-979			
4.394	-642			
4.391	-900			
4.391	-940			

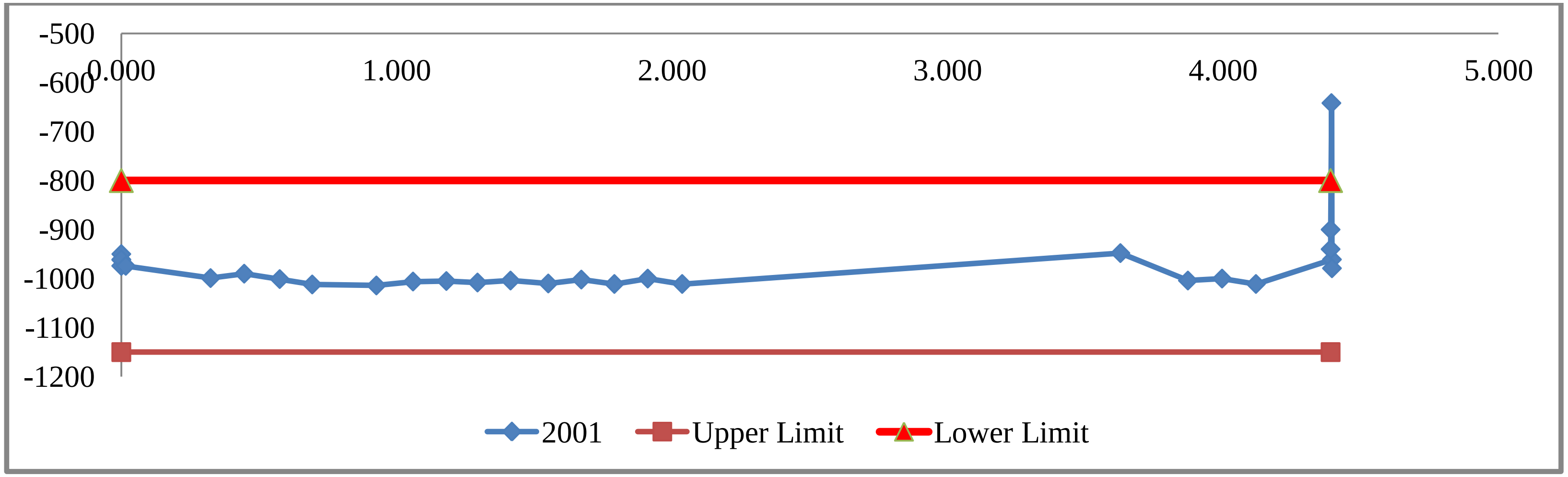


Figure 5: Graph of Protection Potential, mV against Kilometer Post, KP (km)

Table 8: Summary of Sacrificial Anode Cathodic Protection for PMOPL 1 - 8" Platform 1 to Platform

Number of Detected Anode	**Number of Depleted Anode**	**Number Of Anode Depleted**							**Average Depletion Rate, (%/year)**	**Average Remaining Life, (year(s))**
		50%	**60%**	**75%**	**90%**	**95%**	**100%**	**No Report**		
38	26	17	2	3	1	2	1	8	3.563	13

5.1.1.2 Depletion Rate and Protection Potential of PMOPL 2 - 10" Platform 3 to Platform 4

Table 9 below shows the data provide from PCSB PMO on the details of performance of sacrificial anode cathodic protection. The provided data are based on protection potential and percentage of depletion. Depletion rate and the remaining life of the anode were analysed according to the percentage of depletion. Summary of the data are shown in Figure 6 and Table 10.

Table 9: PMOPL 2 - 10" Platform 3 to Platform 4 Sacrificial Anode Particular

Kilometer Post (km)	Protection Potential (mV)	Depletion (%)	Depletion Rate (%/year)	Remaining Life (year)
0		25	3.125	25
0.003	-1009	25	3.125	25
0.02	-1008	50	6.25	8
0.032	-1002	50	6.25	8
0.131	-993	25	3.125	25
0.229	-993	25	3.125	25
0.329	-985	25	3.125	25
0.427	-954	25	3.125	25
0.525	-1006	25	3.125	25
0.531	-664	25	3.125	25
0.588		25	3.125	25
0.626	-640	25	3.125	25
0.669		25	3.125	25
0.864		25	3.125	25
0.965		25	3.125	25
1.062	-1020	25	3.125	25
1.163		25	3.125	25
1.261		25	3.125	25
1.459		25	3.125	25
1.558		25	3.125	25
1.658		25	3.125	25
1.756		25	3.125	25
1.885		25	3.125	25
1.963		25	3.125	25
2.152	-1004	25	3.125	25
2.353		25	3.125	25
4.363		25	3.125	25
5.025		25	3.125	25
5.037		25	3.125	25
5.102		25	3.125	25
5.304		25	3.125	25

6.809	-1043	25	3.125	25
7.503		25	3.125	25
7.669	-1039	25	3.125	25
7.799		25	3.125	25
7.896		25	3.125	25
7.996		25	3.125	25
8.096	-1038	25	3.125	25
8.194		25	3.125	25
8.281		25	3.125	25
8.393		25	3.125	25
8.492		25	3.125	25
8.592		25	3.125	25
8.691		25	3.125	25
8.788		25	3.125	25
8.888		25	3.125	25
8.987		25	3.125	25
9.088	-1029	25	3.125	25
9.289		25	3.125	25
9.386		25	3.125	25
9.484		25	3.125	25
9.582		25	3.125	25
9.781		25	3.125	25
9.881		25	3.125	25
9.979	-1019	25	3.125	25
10.032	-1002	25	3.125	25
10.128	-1000	25	3.125	25
10.134	-1017	25	3.125	25
10.219	-1013	25	3.125	25
10.317	-1013	25	3.125	25
10.416	-1011	25	3.125	25
10.515	-1015	25	3.125	25
10.614	-1019	25	3.125	25
10.627	-1021	25	3.125	25

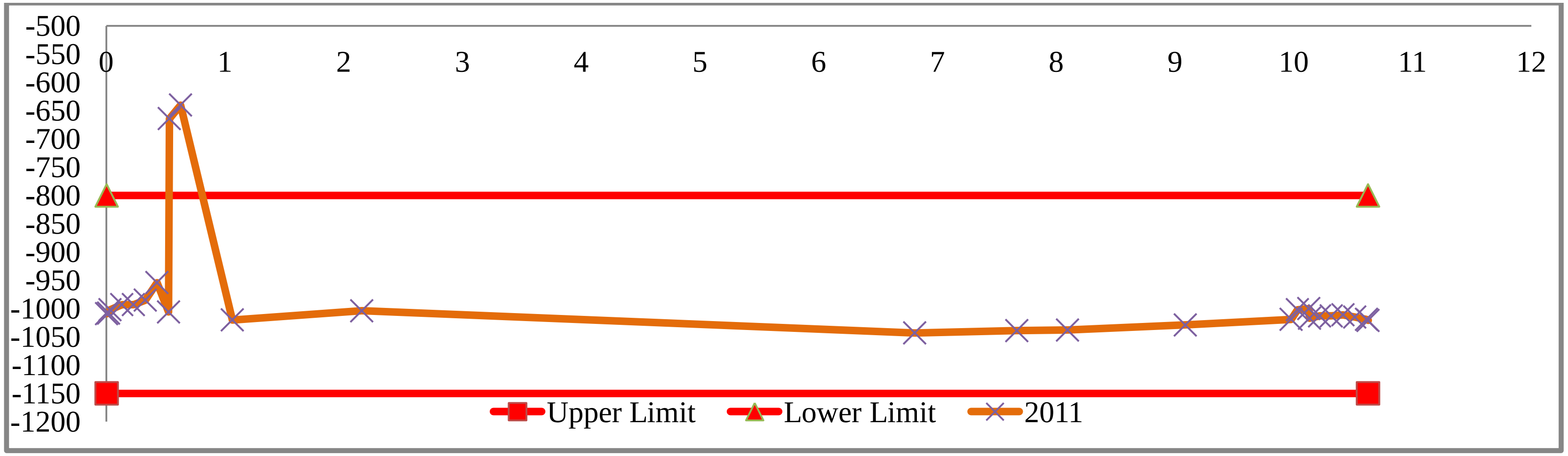


Figure 6: Graph of Protection Potential, mV against Kilometer Post, KP (km)

Table 10: Summary of Sacrificial Anode Cathodic Protection for PMOPL 2 - 10" Platform 3 to Platform

Number of Detected Anode	**Number of Depleted Anode**	**Number Of Anode Depleted**		**Average Depletion Rate, (%/year)**	**Average Remaining Life, (year(s))**
		25%	**50%**		
64	64	17	2	3.223	24

5.2 Sacrificial Anode Cathodic Protection Design

In designing sacrificial anode, DNV RP-B401 is used as reference for the calculation which consist of several parameters such as weight, dimension, current output and total number of anode that has to be installed for certain length of pipeline. In this study, the author has design sacrificial anode for 10 inches and 2.4 kilometer pipeline with environmental condition and industrial purpose as same as PCSB PMO pipeline used for transporting crude oil and gas. There are many types of sacrificial anode differentiated by the size, dimension, shape and where it is going to be installed.

Designing anode either to be welded or as a retrofit anode requires a lot of parameters such as details of pipeline, environmental condition and details of anode itself. Most of the data of pipeline are provided by PETRONAS Carigali Sdn. Bhd. Peninsular Malaysia Operation, PCSB PMO with Private and used in designing sacrificial anode. However, specific details for anode such as dimension, current output etc. are not given by PCSB PMO as they are private and confidential. As a conclusion, the author gathered the data from METEC Group which is one of the fabricator of sacrificial anode cathodic protection.

5.2.1 Corrosion Rate of Sacrificial Anode Cathodic Protection as of Design

In order to proceed with design procedures, the output current of the anode to protect the pipeline must be sufficed and the requirement is depend on the size, weight and dimension. Based on DNV RP-B401, protection potential of the anode must be within -0.8 V to -1.15 V. The required current output is 8.0056 A.

Table 11: Zinc Sacrificial Anode Particular

Anode Type	Zinc
Dimension, mm	
Length, L_a	1100
Width 1, W_t	200
Width 2, W_b	250
Height, H	200
Core diameter, D	50
Slanting length, S	202
Area. m^2	1.28
Weight of anode, kg/anode	337.77 kg
Anode's Current Output, A	19.4 A

Table 12: Aluminium Alloy Sacrificial Anode Particular

Anode Type	Aluminium Alloy
Dimension, mm	
Length, L_a	1100
Width 1, W_t	200
Width 2, W_b	250
Height, H	200
Core diameter, D	50
Slanting length, S	202
Area. m^2	1.28
Weight of anode, kg/anode	129.712 kg
Anode's Current Output, A	19.4 A

Based on the data from PCSB PMO, the corrosion rate is given in terms of depletion rate. Hence, the value of mass loss is calculated with respect to the depletion rate.

Corrosion Rate, % = $\frac{kW}{\mathrm{DAT}}$

k is a constant = 87.6 x 10^3

W = weight loss

W_o = Original Weight

D = Density of metal

A = Area of anode

T = Operational time

5.2.1.1 Corrosion Rate of Zinc Sacrificial Anode

$W_o = 337.77$ kg

A = 12800 cm^2

T = 149019 hours

D = 7.135 kg/cm^3

k = 87.6 x 10^3

$W_{loss} = 9933815.7\ mg$

$$Corrosion\ Rate = \frac{(87.6 \times 10^3)(9933815.7\ mg\ )}{(7.135\ kg/m^3)(12800\ cm^2)(149019)} = \ 63.89\ mm/year$$

5.2.1.1 Corrosion Rate of Aluminium Alloy Sacrificial Anode

$W_o = 129.712$ kg

A = 12800 cm^2

T = 70126.5 hours

D = 8.33 kg/cm^3

k = 87.6 x 10^3

$W_{loss} = 8107000\ mg$

$$Corrosion\ Rate = \frac{(87.6 \times 10^3)(8107000\ mg\ )}{(8.33\ kg/m^3)(12800\ cm^2)(70126.5)} = \ 94.98\ mm/year$$

Based on the results that has been calculated, it is found that corrosion rate of aluminium anode is higher than zinc anode. The value of weight loss are get from the calculation based of number of depletion rate reported during underwater inspection.

The result of corrosion rate is too big because or duration of operational year. Since, the time is in hour and the weight loss is in milligram, the data result in big number.

5.3 Weight Loss Experiment

5.3.1 Corrosion Rate of Aluminium

Table 13: Cleaning Cycle and Mass Loss of Aluminium

Cleaning Cycle	Mass After Immersion	Mass Loss
1	0.2572 - 0.2569	0.0003
2	0.2669 - 0.2558	0.0011
3	0.2558 - 0.2547	0.0011
4	0.2547 - 0.2539	0.0008

$$\text{Area} = \ 1.6\ \text{cm}^2$$
$$\text{Weight Before Immersion} = \ 0.2572\ \text{gram}$$
$$\text{Weight After Immersion} = \ 0.2569\ \text{gram}$$
$$\text{Corrosion Rate} = \frac{\text{kW}}{\text{DAT}}$$
$$\text{Corrosion Rate} = \frac{(87.6 \times 10^3)(0.0033)}{(8.33\ \ \text{kg/m}^3)(1.6\ \text{cm}^2)(24\ \text{hours})}$$
$$\text{Corrosion Rate} = \ 0.903\ \text{mm/year}$$

5.3.2 Corrosion Rate of Zinc Plate

Table 14: Cleaning Cycle and Mass Loss of Zinc Plate

Cleaning Cycle	Mass After Immersion	Mass Loss
1	0.1190 - 0.1187	0.0003
2	0.1187 - 0.1180	0.0007
3	0.1180 - 0.1173	0.0007
4	0.1173 - 0.1168	0.0005

$$\text{Area} = \ 1.31\ \text{cm}^2$$
$$\text{Weight Before Immersion} = \ 0.1190\ \text{gram}$$
$$\text{Weight After Immersion} = \ 0.1187\ \text{gram}$$
$$\text{Corrosion Rate} = \frac{\text{kW}}{\text{DAT}}$$
$$\text{Corrosion Rate} = \frac{(87.6 \times 10^3)(0.0022)}{(7.135\ \ \text{kg/m}^3)(1.31\ \text{cm}^2)(24\ \text{hours})}$$
$$\text{Corrosion Rate} = \ 0.86\ \text{mm/year}$$

5.3.3 Corrosion Rate of Carbon Steel API 5L X65

Table 15: Cleaning Cycle and Mass Loss of Carbon Steel API 5L X65

Cleaning Cycle	Mass After Immersion	Mass Loss
1	2.9060 - 2.9058	0.0002
2	2.9058 - 2.9054	0.0004
3	2.9054 - 2.9049	0.0005
4	2.9049 - 2.9037	0.0012

$$\text{Area} = 3.45\ \text{cm}^2$$
$$\text{Weight Before Immersion} = 2.9060\ \text{gram}$$
$$\text{Weight After Immersion} = 2.9058\ \text{gram}$$
$$\text{Corrosion Rate} = \frac{\text{kW}}{\text{DAT}}$$
$$\text{Corrosion Rate} = \frac{(87.6 \times 10^3)(0.0023)}{(7.86\ \text{kg/m}^3)(3.45\ \text{cm}^2)(24\ \text{hours})}$$
$$\text{Corrosion Rate} = 0.31\ \text{mm/year}$$

5.3.4 Corrosion Rate of Aluminium and Carbon Steel API 5L X65

Table16: Cleaning Cycle and Mass Loss of Aluminium

Cleaning Cycle	Mass After Immersion	Mass Loss
1	0.2107 - 0.2106	0.0001
2	0.2106 - 0.2097	0.0009
3	0.2097 - 0.2085	0.0012
4	0.2085 - 0.2074	0.0011

$$\text{Area} = \ 1.38\ \text{cm}^2$$

$$\text{Weight Before Immersion} = \ 0.2107\ \text{gram}$$

$$\text{Weight After Immersion} = \ 0.2106\ \text{gram}$$

$$\text{Corrosion Rate} = \frac{\text{kW}}{\text{DAT}}$$

$$\text{Corrosion Rate} = \frac{(87.6 \times 10^3)(0.0033)}{(8.33\ \ \text{kg/m}^3)(1.38\ \text{cm}^2)(24\ \text{hours})}$$

$$\text{Corrosion Rate} = \ 1.048\,\text{mm/year}$$

Table 17: Cleaning Cycle and Mass Loss of Carbon Steel API 5L X65

Cleaning Cycle	Mass After Immersion	Mass Loss
1	3.0615 - 3.0612	0.0003
2	3.0612 - 3.0609	0.0003
3	3.0609 - 3.0604	0.0005
4	3.0604 - 3.0603	0.0001

$$\text{Area} = \ 3.51\ \text{cm}^2$$

$$\text{Weight Before Immersion} = \ 3.0615\ \text{gram}$$

$$\text{Weight After Immersion} = \ 3.0612\text{gram}$$

$$\text{Corrosion Rate} = \frac{\text{kW}}{\text{DAT}}$$

$$\text{Corrosion Rate} = \frac{(87.6 \times 10^3)(0.0012)}{(7.86\ \ \text{kg/m}^3)(3.51\ \text{cm}^2)(24\ \text{hours})}$$

$$\text{Corrosion Rate} = \ 0.158\ \ \text{mm/year}$$

5.3.5 Corrosion Rate of Zinc and Carbon Steel API 5L X65

Table 18: Cleaning Cycle and Mass Loss of Zinc

Cleaning Cycle	Mass After Immersion	Mass Loss
1	0.1265 - 0.1260	0.0005
2	0.1260 - 0.1254	0.0006
3	0.1254 - 0.1248	0.0006
4	0.1248 - 0.1241	0.0007

$$\text{Area} = 1.35\ \text{cm}^2$$
$$\text{Weight Before Immersion} = 0.1265\ \text{gram}$$
$$\text{Weight After Immersion} = 0.1260\ \text{gram}$$
$$\text{Corrosion Rate} = \frac{\text{kW}}{\text{DAT}}$$
$$\text{Corrosion Rate} = \frac{(87.6 \times 10^3)(0.0024\ )}{(7.135\ \ \text{kg/m}^3)(1.35\ \text{cm}^2)(24\ \text{hours})}$$
$$\text{Corrosion Rate} = 0.909\ \text{mm/year}$$

Table 19: Cleaning Cycle and Mass Loss of Carbon Steel API 5L X65

Cleaning Cycle	Mass After Immersion	Mass Loss
1	3.0625 - 3.0615	0.0010
2	3.0615 - 3.0612	0.0003
3	3.0612 - 3.0609	0.0003
4	3.0609 - 3.0608	0.0001

$$\text{Area} = 3.51\ \text{cm}^2$$
$$\text{Weight Before Immersion} = 3.0625\ \text{gram}$$
$$\text{Weight After Immersion} = 3.0615\ \text{gram}$$
$$\text{Corrosion Rate} = \frac{\text{kW}}{\text{DAT}}$$
$$\text{Corrosion Rate} = \frac{(87.6 \times 10^3)(0.0017)}{(7.86\ \ \text{kg/m}^3)(3.51\ \text{cm}^2)(24\ \text{hours})}$$
$$\text{Corrosion Rate} = 0.224\ \text{mm/year}$$

According to weight loss result of single metal, aluminium has the highest corrosion rate compared to zinc and carbon steel with weight loss of 0.0033 gram and the corrosion rate is 0.903 mm/year.

Same goes to the coupled metal which is zinc and carbon steel and aluminium and carbon steel. The result is also the same with aluminium is the highest which is 1.048 mm/year. Corrosion rate of zinc is 0.909 mm/year which is also high. However, corrosion rate of carbon steel that is coupled with zinc is higher compared to the one attached with aluminium.

5.4 Linear Polarization Resistance

Below is the result of Linear Polarization Resistance (LPR) which the data is taken in 24 hours.

Table 20: Corrosion Rate of Zinc and Aluminium based on Linear Polarization Resistance

Corrosion Rate (mm/year)	
Zinc	**Aluminium**
1.154529	19.51020987
1.486147	13.83802999
0.752864	15.04627179
0.901166	13.79983237
0.88608	12.13073818
0.675367	9.492333629
0.894777	10.193571
0.957544	6.593893293
0.695684	5.938144621
0.819968	6.030395592
0.753488	5.743527553
0.806788	5.675600059
0.923345	4.941015639
0.775421	5.432302936
0.762297	2.096783306
0.787464	1.954793426
0.783918	2.257314052
0.894766	2.187207086
0.770761	2.26597138
0.767616	2.205123716
0.753165	1.961197887
0.702486	3.826554579
0.739294	1.815544233
0.765865	1.516261412

0.817002	1.39167658
0.85788	1.485563852
0.85294	1.420974119
0.914424	1.533692054
0.912217	1.387263139
0.909674	1.430401113
0.938443	1.510271467

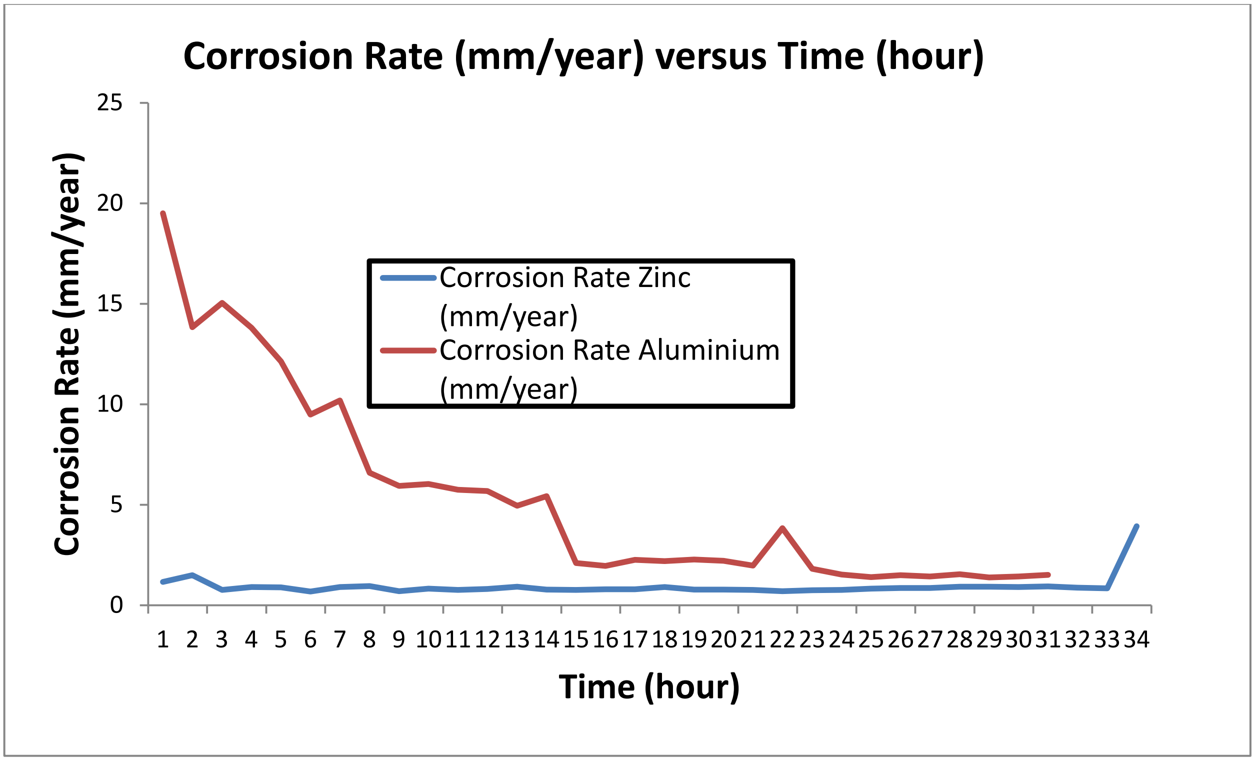


Figure 7: Graph of Linear Polarization Resistance

Based on Linear Polarization Resistance experiment, it is found that aluminium has the highest corrosion rate compared to zinc. Initial part of the experiment shows the data for aluminium is slightly high then decrease until it achieve stable corrosion rate. Data for zinc is maintained from beginning until the end. However, corrosion rate of zinc is higher at the end of the experiment because of the thickness of zinc is too thin. Zinc tends to lose some part of surface area.

CHAPTER 6:

CONCLUSION and RECOMMENDATIONS

This study has meet all the objectives which is o study the rate of corrosion of zinc and aluminium when in contact with carbon steel in seawater environment and to study effective metal as sacrificial anode cathodic protection for subsea pipeline. Based on all the results from field data, design data and laboratory simulation, this study conclude that aluminium has the highest corrosion rate compared to zinc. It is also being proved in electro-negativity series that explain active metal is more likely to corrode when attached with noble metal. In this study, carbon steel API 5L X65 is chosen to be the noble metal as the material also is used to build pipeline.

As the conclusion, aluminium is the effective metal to be as sacrificial anode cathodic protection for subsea pipeline.

RECOMMENDATIONS

In future, this study able to provide an extra assessment on different metals other than zinc and aluminium, for example magnesium and titanium since these metals is quite reactive and located in the range with aluminium and zinc in electro-negativity series.

In addition, this study could provides a result from Scanning Electron Microscope, SEM and Energy Dispersion X-Ray, EDX. SEM can perform high magnifications and generate high-resolution images for small objects. The data obtain are precise and it is very effective for microanalysis. Using the same equipment, the Energy Dispersion X-Ray (EDX) was also obtained to detect the number of chemical compositions exist on the sample used. The data generated during analysis produce a two-dimensional image and information about the sample texture, chemical composition and the orientation of materials in the sample.

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