Study on Cathodic Protection Principles and Requirements of Underground Steel Pipes (Concept and Laboratory/model Scale)

by

Mohamad Fadhly Bin Ab. Ghani

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

June 2004

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CERIFICATION OF APPROVAL

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Mechanical Engineering Programme
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BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

Approved by,

(Dr. Othman Mamat)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
June 2004

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 concept as specified in the references and acknowledgements, and that the original work contained herein have not been under taken or done by unspecified sources or persons.

MOHAMAD FADHLY BIN AB. GHANI

ABSTRACT

The objective of this project is to study the cathodic protection principle and requirements of underground steel pipes by using concept and laboratory experiments.

Cathodic protection (CP) is a means of preventing a metallic object which is either buried in the ground or immersed under water from corrosion. It is basically an electro-chemical process. In understanding CP, basic knowledge about several subjects, chemistry, electricity, metallurgy and mathematics will be required. The basic principal of CP is to turn a metals surface into a cathode (cathodic), hence the name cathodic protection. A metals surface, buried or immersed, can contain anodic and cathodic areas, corrosion only occurs at the anodic areas, therefore if a metal objects surface can be turned into a cathode over its entire surface, then corrosion can be prevented on the metallic structure. Corrosion is not actually eliminated; it is moved to a known location by adding an anode which is designed to slowly corrode in a controlled manner, thus leaving the intended metallic structure intact.

In order to achieve the objectives, project planning using Gantt chart has been developed. It started with Literature Study mainly on the underlying theories of cathodic protection principles. Experiment will then be conducted to:

1. Test several possible sacrificial anodes and select the most suitable one.
2. Test the efficiency of cathodic protection on buried steel pipe using the chosen alloy as the sacrificial anode. The result will then be compared to the buried steel pipe without cathodic protection (in terms of corrosion rate).

Cathodic protection is a promising corrosion inhibitor with the advantages such as cut maintenance expense, cut replacement costs, decrease labor costs, stop rust and corrosion, less expensive than coatings, and easy to install.

ACKNOWLEDGMENT

In the name of ALLAH, the Most Graceful and Most Merciful,

First, I would like to express my greatest gratitude to my supervisor, Dr. Othman Mamat for his expert guidance, attention and suggestions, supports and advices regarding the project and difficulties faced during the project execution.

Special thanks to all Materials Lab and Chemical Lab technicians, for their guidance, supports and concern during the project works especially during laboratory experiments practices.

Not forget to mention, I would like to thank to my external supervisor from SIRIM and to my internal supervisor, Mr. Saravanan, from UTP Mechanical Engineering Department whom both have given me advises and recommendations in improving this project.

I am grateful to Ms Haly Liza, Mr. Azarudin Azral, and Mr Mohd Zakry because of given freely of their time to discuss together in improving materials of my project.

To my family love and thank you. Without your enormous support and concern, all my effort in preparing this final year project would have not successful.

Last but not least, my appreciation goes out to the individuals or groups that have helped me in any possible way to complete this project.

Above all, I would like to thank God for making it possible for this project until this.

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CHAPTER 1
INTRODUCTION

1.1 Background Of Study

Although corrosion cannot always be completely prevented, judicious use of the proper materials of construction and good design practices can maintain corrosion rates within tolerable limits.

For decades, impressed current and galvanic cathodic protection systems have been successfully used to protect buried pipe-lines, ship hulls, off shore oil platforms, heat exchangers, under-ground tanks, and many other facilities exposed to a corrosive environment.

Therefore, there is a need for continuous improvement of new cathodic protection design to optimize parts protection from corrosion. The protection profiles of new and older cathodic protection system can be improved through the use of new properly designed system.

This study will focus on the protection of underground steel pipes using sacrificial anode method. Comparison between underground steel pipes which are cathodically protected and the one which is exposed to environmental corrosion without protection will be done. Upon completion of the study, the outcome will be what the best method to cathodically protect metal parts is. The recommended cathodic protection should also comply with current regulation and can be implemented.

The first half of the project duration is mainly dedicated towards doing researches and doing literature reviews, finding information sources from the resource center and also from the internet in order to get prepared before conducting the actual experiment.

Entering the second half of the project duration, the practical work has started. The background of study is emphasizing on cathodic protection circuit in terms of laboratory work. Initially, the study covers the actual cathodic protection circuit, which involves deep ground bed anode, junction box and rectifier, but for experimental work purposes, the circuit is represented by a corrosion cell circuit. The corrosion cell will involve the tested material which is a steel pipe, an anodic material and electrolyte. The actual field setup for cathodic protection circuit is shown in Figure 1.1.

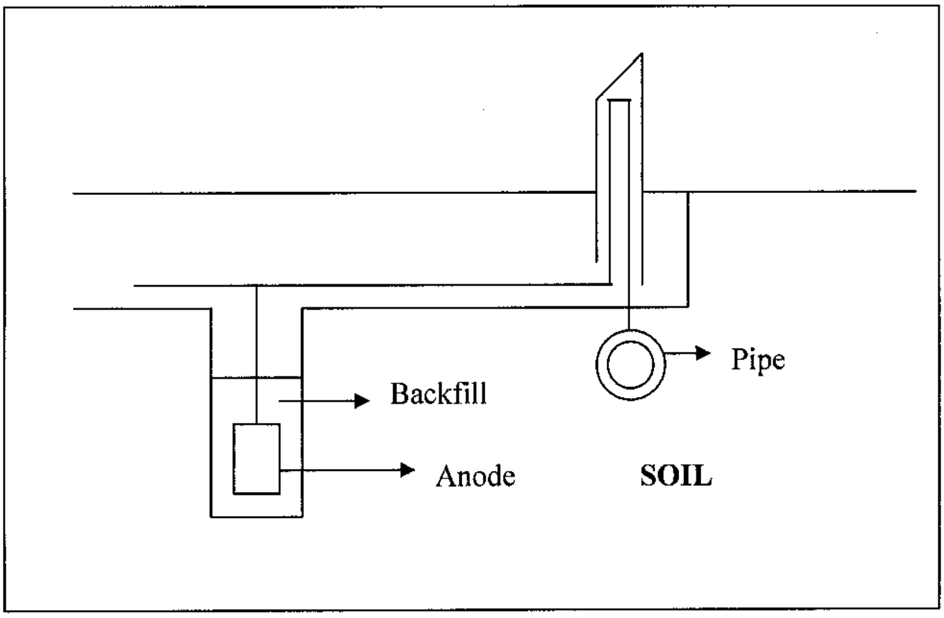


Figure 1.1: Design for Cathodic Protection System for an underground steel pipe

For experimental purposes the setup in Figure 1.2 was constructed to represent the actual condition. The advantages of such representation are.

1. Inexpensive screening to reduce expensive field testing.
2. Study of the effects of environmental variables.
3. Study of the corrosion accelerating for protective effects of various anode cathode surface area ratios.

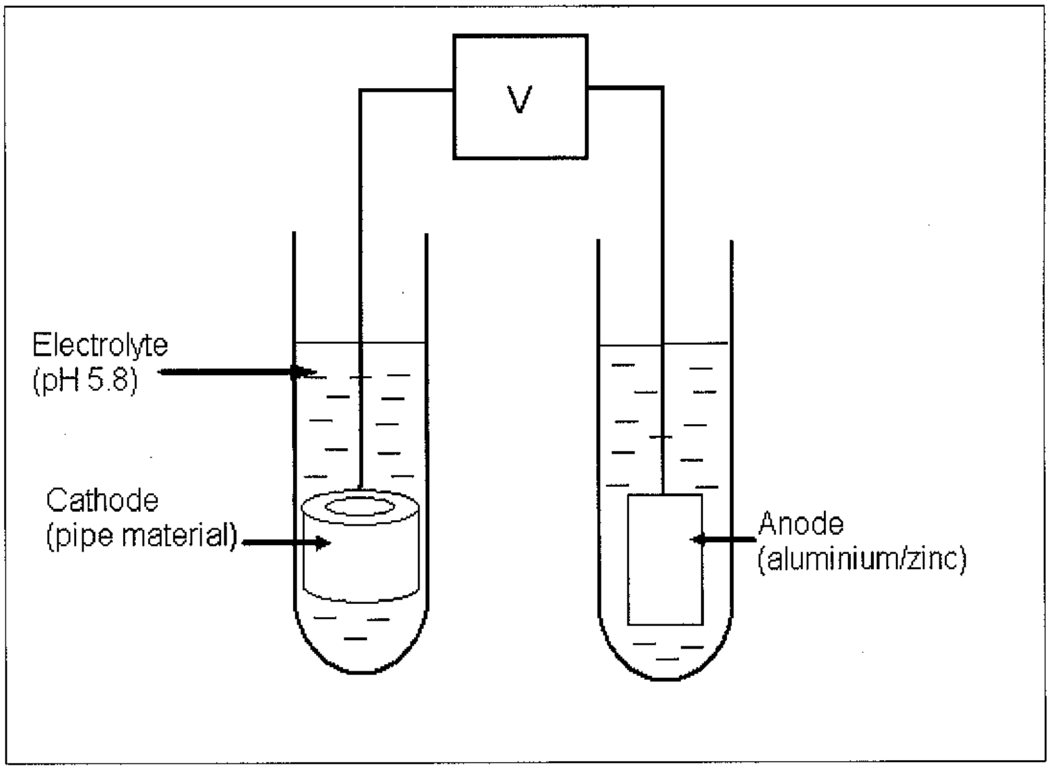


Figure 1.2: Electrochemical Corrosion Cell representing

From both the figures (Figure 1.1 and Figure 1.2) the relationship between both can be referred to Table 1.1 below.

Table 1.1: Relationship between Real Cathodic Protection Circuit and Lab Scale Circuit

Main elements	**Real Cathodic Protection Circuit**	**Lab scale representatives**
Electrolyte	Soil with pH 5.8 Which is acidic	Hydrochloric Acid with pH 5.8
Anode	Deep Grounbed anode with galvanic anode alloy	Anode specimen Zinc / Aluminium
Cathode	Surface of steel pipe	Steel pipe specimen

Thus, in order to identify the suitable sacrificial anode that able to protect the anode specimen, several materials is short listed to be tested via the corrosion cell experiment. The study is basically to measure the potential of each selected metals in order to know the corrosion rate, where, from the corrosion rate, then only the better sacrificial anode that protect the cathode can be determined. Besides that, the study scope also considers the soil pH as one of the case study. Therefore, by knowing the soil potential and measuring its pH, electrolyte solution of the similar pH can be provided in order to promote the soil environment to those materials tested in the circuit.

The AUTOLAB software that has the function to perform electrochemical measurement will be used to compare the experiment result since it could gives several readings, such as the potential and corrosion rate.

1.2 Problem Statement

The problem statement is to study the corrosion effect on the external surface of an underground (buried) steel pipe. This is due to the external surface of the pipe that contact with soil will have a positive natural potential, thus it will released electrons to the ground and resulting the pipe to corrode.

1.2.1 The Significant Of The Project

Cathodic protection is achieved by supplying electrons to metal structure to be protected. Different metal requires different ways to cathodically protect. Know how in designing the proper protection is necessary in extending life of buried (underground) steel pipes. In order to achieve this, deep understanding of the cathodic protection principles are vital in order to design a more reliable (optimized) system for the pipe's protection.

Series of laboratory experiments are conducted to test a combination of anode-cathode metals, and corrosion characteristics. This requires knowledge on how to operate the equipment, how to conduct the experiments, how to handle the metals and others.

The completion of this project gives an overview on how the soil influences the corrosion at the surface of underground steel pipe that has contact with it. The study clearly shows that without cathodic protection, the soil resistivity will act as electrolyte that causes the pipe surface which has positive natural potential to release its electrons. This reaction will cause the pipe to corrode. Thus, with cathodic protection that uses sacrificial anode concept, a material of higher reactivity will become an anode to the pipe surface and the soil becomes the electrolyte to complete the circuit. Therefore, we can see that the significant of this project is to study on how the cathodic protection plays its role in protecting the pipe and how effective does this method works to overcome this corrosion phenomenon. This will help to control the corrosion rate and predict the life span of a pipe that prone to this type of corrosion cause.

The basic knowledge of underlying theories, including electrochemical reactions, corrosions and galvanic series, are important for the analysis of the experimental data collected. The standard EMF (reactivity) series for metal using hydrogen electrode as reference electrode is shown in Table 1.2, the metals of interest are highlighted in the table.

Table 1.2: Standard EMF Series for Metals

	Metal-metal ion equilibrium	Electrode potential vs. normal hydrogen electrode at 25^0C
Noble or cathodic	$Au\text{-}Au^{+3}$	+1.498
	$Ag\text{-}Ag^{+1}$	+0.799
	$Hg\text{-}Hg_3^{+2}$	+0.788
	$Cu\text{-}Cu^{+2}$	+0.337
	$H_2\text{-}H^+$	0.000
	$Pb\text{-}Pb^{+2}$	-0.126
	$Sn\text{-}Sn^{+2}$	-0.136
	$Ni\text{-}Ni^{+2}$	-0.250
	$Cd\text{-}Cd^{+2}$	-0.403
	$Fe\text{-}Fe^{+2}$	-0.440
	$Cr\text{-}Cr^{+2}$	-0.744
	$Zn\text{-}Zn^{+2}$	-0.763
	$Al\text{-}Al^{+3}$	-1.662
	$Mg\text{-}Mg^{+2}$	-2.363
	$Na\text{-}Na^{+1}$	-2.714
Active or anodic	$K\text{-}K^{+1}$	-2.925

1.3 Objectives Of Study

The objectives of this study are:

1. To study the principles of Cathodic Protection of underground pipe.
2. To construct a laboratory experiment to test the effectiveness of cathodic protection of a steel pipe and to compare it with an unprotected one.
3. To compare the result of the laboratory scale experiment and the real CP system and recommend ways to improve its effectiveness.

1.4 Scope Of Study

This project requires the understanding of the cathodic protection principle and its importance in protecting certain metal parts. This study are focused mainly on the cathodic protection principle and corrosion characteristic of metals when protected with the cathodic protection.

Literature study via books, journals, Internet, etc are conducted to gather information on the theories and to enhance understanding of the study. Laboratory experiments are performed to study the corrosion characteristic of a steel pipe connected to a sacrificial anode. Collected data are analyzed theoretically and graphically using Microsoft Excel software. The integration of the outcome of the corrosion characteristic is used as the based to choose the most optimum cathodic protection combination.

CHAPTER 2

LITERATURE REVIEW

2.1 Corrosion Of Metals

Understanding the principles of cathodic protection systems is based upon understanding the nature of the corrosion process. The corrosion of metals is an electrochemical process. That is, it is an electrical circuit where the exchange of electrons (electricity) is conducted by chemical reactions in part of the circuit. These chemical reactions occur at the surface of the metal exposed to the electrolyte. Oxidation reactions (corrosion) occur at the surface of the anode and reduction reactions (protection) occurs at the surface of the cathode [4]. Corrosion control systems which relocate these oxidation reactions, by making the protected structure a cathode in a larger corrosion cell, is called a cathodic protection system. The cathodic protection anodes are installed to become the anode in this larger corrosion cell and provide the location for all oxidation reactions in the cell.

The corrosion resistance of metals and alloys is a basic property related to the easiness with which these materials react with a given environment. Corrosion is a natural process that seeks to reduce the binding energy in metals. The end result of corrosion involves a metal atom being oxidized, whereby it loses one or more electrons and leaves the bulk metal. The lost electrons are conducted through the bulk metal to another site where they are reduced. In corrosion parlance, the site where metal atoms lose electrons is called the anode, and the site where electrons are transferred to the reducing species is called the cathode [5].

2.2 Cathodic Protection

Cathodic protection (CP) is an electrochemical method used to prevent or control corrosion of buried or submerged metallic structures. CP systems are active systems which rely on the application of electric current to control corrosion. It also means the utilization of the electrical properties of corrosion of metallic substances to provide a system for the protection of steel underground storage tanks, metallic piping or any other buried metallic structure, to extend their useful life (in other words to prevent underground steel structure from rusting) [7]. There are two types of cathodic protection, galvanic protection and impressed current.

2.3 Galvanic Cathodic Protection System

A galvanic cathodic protection system for underground steel pipes, consists of sacrificial anode(s) fixed to the pipes, and provides specified wiring for an inspection station installed near the surface of the ground. Galvanic systems have limited life spans during which the sacrificial anode will continue to degrade and protect the piping. When the sacrificial anodes are no longer capable of protecting the tank or piping, they will lose their protection and begin to corrode.

2.4 Sacrificial Anode System

Further studies on cathodic protection principles reveals that the protection can be conducted in two different methods:

1. Using a rectifier to supply direct current to the protected parts.
2. The use of sacrificial anode to supply required electrons.

Sacrificial anode systems are based on a metals position in the galvanic series. The galvanic series is a list of metals arranged according to there relative corrosion potentials in a specific environment.

Metals towards the top of galvanic series are more prone to corrosion attack or least noble, and the metals at the base of the series are least prone to corrosion or most noble. If connections are made with one of the metals near the top of the table with one near the bottom of the table, then the metal picked from the top of the series will corrode or be sacrificed in preference to the metal nearer the bottom of the series, hence the name sacrificial anode [2].

Because the galvanic system relies on the natural difference in electrical energy between the two metals, the current output levels from the anode are relatively low, depending on which type of environment (soils) or electrolytes that the anodes are placed in. This makes the galvanic type of system only suitable for soils or water which has a lower resistivity. There are some exceptions to this where sacrificial anodes are still beneficial even within a higher resistivity environment such as difficult to access structures and offshore steel jackets [2].

For the time being, it was found that sacrificial anode systems are more reliable than impressed current systems because there are fewer components to go wrong with this type of system and no power supply required.

Basically the sacrificial anode system comprises of:

1. Anode, usually solid block of Magnesium, Zinc or Aluminium.
2. Cable connection to the structure/parts.
3. Test facility to monitor the anode current output.
4. Isolation material between above / below ground structures.

Requirement or sacrificial anode [4]:

1. The corrosion potential of the alloy must be sufficiently active (negative) to drive protective current through the electrolyte. The higher the resistance of the electrolyte and the greater the separation of anode and structure, the more negative must be the potential of the anode.
2. Polarization at the sacrificial anode must be low enough to permit current flow.
3. The electrochemical equivalent (output) of the anode alloy, should be high.
4. Efficiency of the alloy (percentage of output delivered in practice, should be high.

Besides the major components, there are additional systems that act as a supplement to the cathodic protection which are:

1. Anode consumption optimizer – anode are backfilled with conductive material (granulated coke etc).
2. Coatings of protected parts.

Compared to anodic protection system, cathodic protection poses several advantages in properties:

Applicability

- Metals – all metals and alloys.
- Solution corrosivity – weak to moderate for practical systems.

Comparative cost

- Installation – lower
- Maintenance – lower
- Operation – higher
- Throwing power – low

Applied current

- Higher – depends on cathodic reduction current.

In designing cathodic protection system, several factors need to be considered.

Potential gradients:

- Cathodic over voltage at the cathode.
- Ohmic potential charge around the cathode structure.
- Ohmic potential charge through the intermediate electrolyte.
- Ohmic potential charge around the anode.
- Anodic over voltage at the anode.

Current and potential distributions on the protected structure:

- Current originates from finite anode locations. Different points on the structure have variable access to current due to differing distances to the nearest anode surface.
- Solution environments for cathodic protection are of intermediate to low conductivity, structure potentials tend to be nonuniform.
- Protected structures are geometrically complex, thus current from the anode(s) often has difficult access to remote or shielded surface locations on the cathode structure.

Sacrificial anodes:

- The corrosion potential of the alloy must be sufficiently active to drive protective current through the electrolyte. The higher the resistance of the electrolyte and the greater the separation of anode and structure, the more negative must be the potential of the anode.
- Polarization at the sacrificial anode must be low enough to permit current flow.
- The electrochemical equivalent (output) of the anode alloy, which is the charge theoretically available to provide galvanic current per unit mass of the alloy, should be high.
- The efficiency of the alloy, which is the percentage of the output delivered in practice, should be high.

For effective cathodic protection system, proper designing is important. Several design considerations that should be concentrated [5]:

- Area to be protected - Calculation of the exposed area to be protected.
- Polarized potential - Determining the appropriate polarized potential and current density required to achieve this potential.
- Current demand - The product of the area and corresponding current-density requirement.
- Anode consumption - Determining the require weight of anode from the known consumption rates for the calculated current demand.

- Anode number and distribution - The usage of several anodes to give uniform current distribution.
- Anode resistance - Calculated from the number and distribution of anode.
- Design output current - From the anode resistance, R and driving voltage, E, of the selected sacrificial anode, the design output current can be calculated from Ohm's law:

$$E=IR \qquad \text{(Equation 2.1)}$$

2.5 Electrolyte Resistivity Measurement

Resistivity is the property of a material which determines the electrical resistance between two points within the material. The most common units of resistivity are ohm-centimeters and ohm/cubic centimeters, which are equivalent. Many factors in the operation of cathodic protection systems are dependent upon the resistivity of the electrolyte [9].

The corrosivity of the environment is generally higher when the resistivity is low. The output of both sacrificial anodes and impressed current anodes is also dependent upon the resistivity of the environment.

The resistivity of soil environments depends upon the amount of moisture present and is subject to wide variations. These commonly experienced variations in soil resistivity affect the operation of cathodic protection systems, manifesting in variations in structure-to-electrolyte potentials or rectifier outputs measured during routine system inspections. Electrolyte resistivity measurements are taken to determine the cause of improper system operation [10].

The measurement of electrical resistivity requires that four electrodes be placed in contact with the surface material. The geometry and separation of the electrode array are selected on the basis of the application and required depth of investigation [11]. The layout is show in Figure 2.1

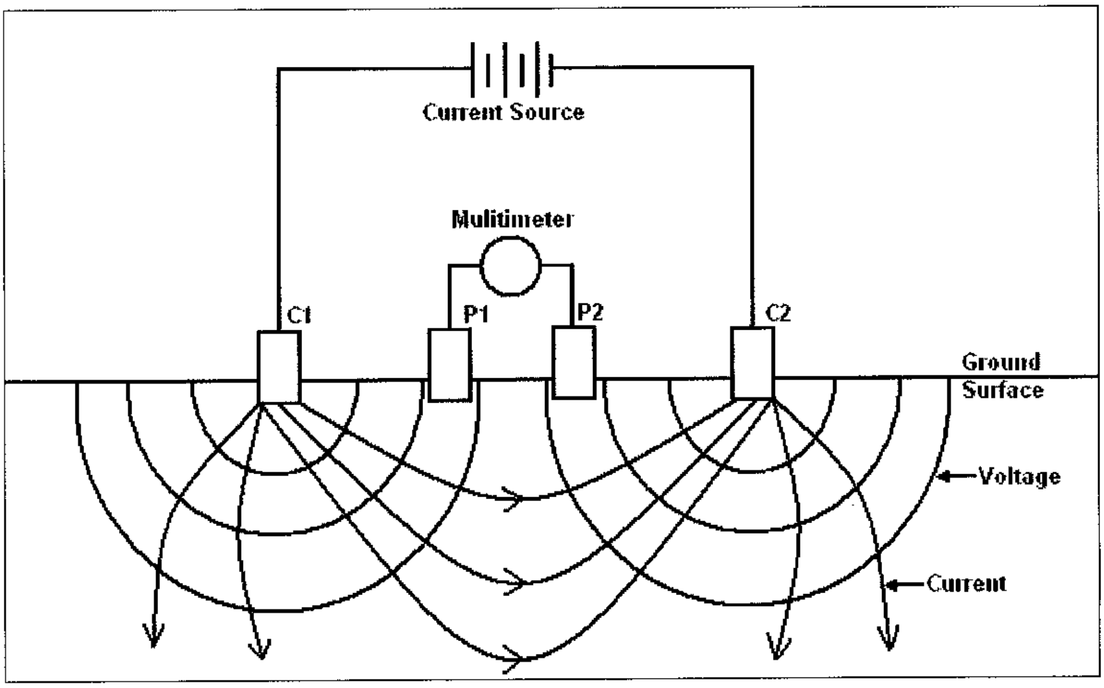


Figure 2.1: Direct current resistivity method for subsurface investigation

CHAPTER 3

METHODOLOGY

3.1 Procedure Identification

A few things need to be done as to meet the objectives of this project:

- Literature study on the theory of cathodic protection, electrochemical reactions, corrosion principles, etc. (sources: books, journals, articles, web pages and laboratory procedure).

- Laboratory experiments to test the combination of anode-cathode metal (steel pipes and its anode) for corrosion characteristic. The interest of the experiments would be the corrosion characteristic, and the rate of corrosion.

- Analysis of the experimental data in order to come out with the best layout for cathodic protection and the most optimum ways to implement it. Some graphical analysis using Microsoft Excel is expected to exhibits the findings and comparisons of the various combinations.

- Gantt chart is used for project monitoring purposed to ensure the smoothness of the study. The project is divided into two semesters and there are several milestones to be completed.

3.2 Simplified Experimental Procedure (initial)

The initial plan to investigate the effectiveness of sacrificial anode is using actual field condition simulated in corrosion chamber. The proposed procedures are:

1. A laboratory scale model of underground steel pipe exposed to the environment is to be constructed using an aquarium filled with soil.

2. The model which contain soils, buried steel pipe and its sacrificial anode cathodic protection system will then be exposed to the environment (rain, sunshine etc) to simulate real world corrosive environment.
3. The experimental setup will be exposed to such condition for a fixed period of time (two to three month) while being monitored.
4. When the period end, the steel pipe will then be dig up and brought to the laboratory for further analysis.
5. The result will then be compared to buried steel pipe exposed to the same condition but without cathodic protection system.

However, several problems have been encountered in order to proceed with the project. Among the trouble shooting findings are:

- Problem in getting Cathodic Protection Package
- Problem in determining sacrificial anode type
- Hard to purchase some types of materials
- Impracticality to run experiment in actual scale
- Problem in sizing, installation and finding medium
- Too wide scope which involves pipe modeling and cathodic protection

3.3 Alternative Solution

A laboratory experiment is conducted. It represents the real case of cathodic protection. This involves small scale work. To select the anode, a corrosion cell is being set-up. The specimen will be tested in a beaker acting as cathode, and other types of tested anode will be connected to it. Both electrodes are placed in electrolyte medium. This would give a corrosive environment to allow the cathodic protection to take place in controlling the corrosion rate of the specimen. The electrolyte however, has to be made of solution which has the same resistivity of the soil sample that being taken from the potential construction area.

After the anode is able to be determined, the chosen anode will be connected to the pipe sample to complete a cathodic protection circuit and will be run in the corrosion chamber. This will allow a clearer view on how does the corrosion took place at the outer surface of the pipe and how does the cathodic protection plays its role.

Basically, for both experiments, which are the corrosion cell and the cathodic protection small scale circuit, a control set of experiment will also be conducted simultaneously with the purpose to compare the results between the cathodically protected specimens with the non-protected. The following are the sequential procedures that being carried out:

a) Specimen material is purchased.
b) Soil sample at the potential pipe construction area is taken.
c) By using pH meter, pH of the soil is measured.
d) Solution of the same pH as the soil is prepared as electrolyte.
e) By using potentiostat, the potential of each sacrificial anode and the specimen material is measured.
f) By using AUTOLAB, the potential for both materials is measured to determine the corrosion rate for each.
g) A complete corrosion cell is set-up by using the specimen as cathode, the Zn as anode and the prepared solution as electrolyte.
h) Another reference set of corrosion cell is set-up to compare the results for both.
i) The observation is noted and the material is being inspected.
j) Step (g) until step (i) are repeated but with Aluminum as the anode electrode.

3.4 Measurement Of Corrosion Rate By AUTOLAB Application

The purpose of this experiment is to measure the corrosion rate of pipe specimen using the standardized apparatus of workstation and AUTOLAB software. The result will be considered a basis for further experiment using the specimen.

3.4.1 Procedures

In conducting this experiment, the procedures are as follows [14]:

i. Samples of pipe specimen (cut and grinded) were prepared.

ii. The surface area (cm^2), equivalent weight and material density (g/cm^3) of each sample were measured and calculated.

iii. Solutions with pH equivalent to the actual soil were prepared as the corrosion solution.

iv. The samples were clipped and connected to the WE electrode and S lead (using 3-electrode set-up).

v. The samples, RE and CE were dipped into the beaker containing 0.1M HCl and the experiment was started.

vi. On the Autolab, the GPES software was launched.

vii. The menu 'Method' > 'Linear sweep Voltametry' > 'Normal' was selected and on the 'Edit Procedure ' window, the following setting were keyed in:

No. of scan: 3
Standby potential: 0V
Begin potential: -0.1V
End potential: 0.1V
Scan rate: 0.005 V/s or lower
Define vertex potential wrt OCP: select 'X'
Time to wait for OCP: 10s or 0s
Surface area: the surface area calculated
Tafel plot: select 'X'

viii. Current range of 1mA was selected on the PGSTAT30 panel.

ix. The measurement were started by selecting menu 'Analysis' > 'Corrosion Rate'.

x. Predetermined data for surface area, equivalent weight and density were entered.

xi. 'Tafel slopes' option and 2 markers were set on the both the anode and cathode branch of the curve.

xii. 'Start Fit' button was clicked and the results obtained were recorded.

xiii. The experiment was repeated for the other two coated samples.

xiv. The results for each of the sample with different type of coating were compared and commented.

3.5 Cathodic Protection Laboratory Test On Pipe Specimen

3.5.1 Procedures

In conducting this experiment, the procedures are as follows [13]:

i. A solution of 1M of HCL acid with pH 5.8 was prepared by titrating it with a 0.2M NaOH solution.

ii. The mass of the specimen and sacrificial anode were measured and recorded.

iii. A closed circuit consisting of the pipe specimen, sacrificial anode and voltmeter was constructed.

iv. The initial reading of the voltmeter was recorded.

v. Another set of experiment was set up as a controlling apparatus consisting of a pipe specimen alone immersed in the HCL solution.

vi. The experiment was left for 10 days before taking the final specimen and anode mass. The measurement was taken for several days interval to observe the change of mass.

vii. The experiment was repeated using zinc as a sacrificial anode to replace Aluminum.

The initial readings of all specimens used are recorded in order to compare it with the experiment result (aluminium as sacrificial anode):

Table 3.1: Initial Reading for Experimental Specimens (Anode = Aluminum)

Item	Mass
Pipe Specimen 1 (protected)	79.38g
Pipe Specimen 2 (unprotected)	76.36g
Anode 1 (aluminium bar)	28.08g
Anode 2 (aluminium bar)	32.10g

Initial readings (zinc as sacrificial anode):

Table 3.2: Initial Reading for Experimental Specimens (Anode = Zinc)

Item	Mass
Pipe Specimen 1	79.01g
Pipe Specimen 2	76.05g
Anode 1 (zinc plate)	11.57g

3.6 Tools Required

Several tools and materials are required in order to conduct this experiment and are listed as follows:

- Equipment: Metal cutting machine, grinding machine, microscope, pH measuring device, beakers, voltmeter, AUTOLAB workstation, weight measuring device.
- Materials : Anode metals (aluminium & zinc alloys), steel pipe, HCL solution, NaOH solution, pH paper.
- Software : Microsoft Excel, AUTOLAB.

3.6.1 Software – AUTOLAB

AUTOLAB combined with the software is a computer-controlled electrochemical measurement system. It consists of a data-acquisition system and a potentiostat/galvanostat. Different components of the AUTOLAB-system are controlled by the computer, as shown in figure 3.1.

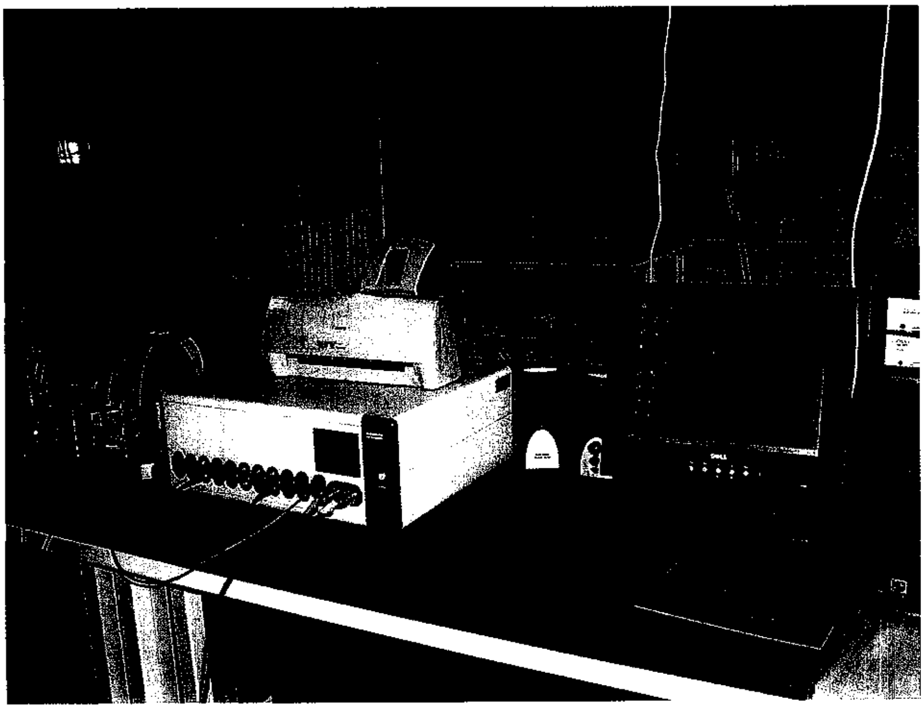


Figure 3.1: AUTOLAB Workstation

The electrochemical cell consists of the following 4 cell cables:

working electrode	WE	(red)
sense electrode	S	(red)
reference electrode	RE	(blue)
counter electrode	CE	(black)

There are 4 connectors on the front panel of PGSTAT30. The cable that connects to the WE and CE electrodes is plugged into the WE/CE socket while the cable with the cell pod (leading to the RE, S and optionally WE2 connects to the RE/S socket. For a three-electrode set-up, WE and S lead are both connected to the WE electrode.

The settings of the AUTOLAB with PGSTAT30 on power-up are pre-defined. The cell is switched on and the current range 1mA is selected.

a. Ag/AgCl Reference Electrode

The electrode is placed inside the reference bridge tube, a compartment filled with 3 mol KCL solution which provides optimum positioning of the reference electrode. The electrode should always contain enough solution during the measurement. The electrode is connected to the blue-color plug of cell cable.

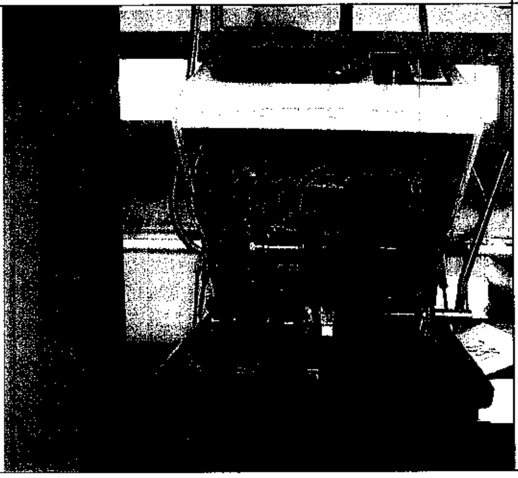
b. Stainless Steel Counter Electrode

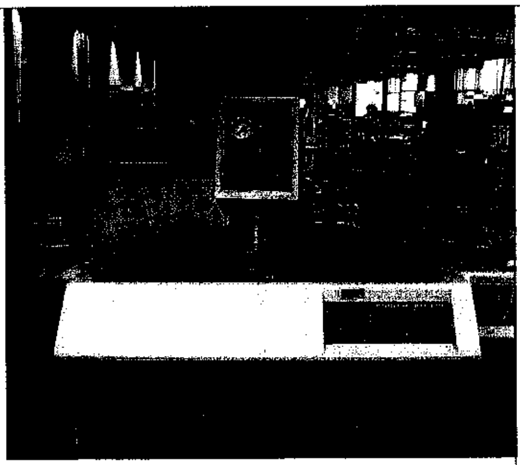
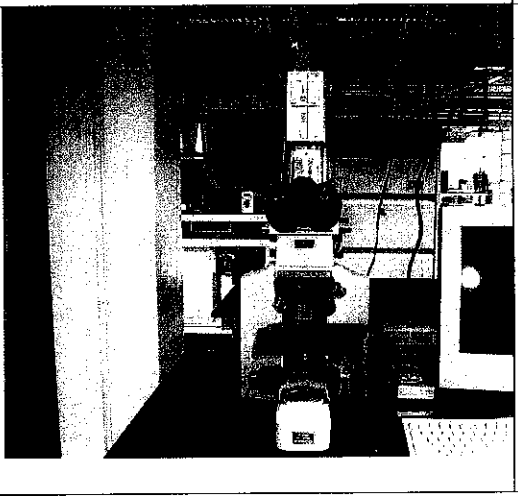
It serves to supply the current flowing at the working electrode during the test. Used in the electrode holders.

3.6.2 Hardware

In conducting the experiment, several equipments are utilized to accomplish the result, as shown in table 3.3.

Table 3.3: Major hardware in conducting the experiment

Hardware	Picture	Description
Weight measuring device		Initial and final weight measuring of anode and cathode used in the experiments.
pH analyzer		To obtain precisely pH 5.8 for the acidic solution to match with the actual soil pH.
Metal cutting machine		To shape the pipe specimens into proper size to ease the completion of a lab scale experiment.

Grinding machine		To remove the outer protective layer of pipe specimen in order to know the effects of sacrificial anode alone in protecting pipe specimens.
Microscope		To analyze the surface of pipe specimens and anode before and after the completion of the experiment.

3.6.3 Specimen

The main item for this experiment is a steel pipe with chemical composition as shown in Table 3.4 and dimension as shown in Table 3.5 [11].

Table 3.4: Chemical composition (max %) for type S (seamless pipe)

Elements	Percentage (%)
Carbon	0.25
Manganese	0.95
Phosphorus	0.05
Sulfur	0.045
Copper	0.40
Nickel	0.40
Chromium	0.40
Molybdenum	0.15
Vanadium	0.08

Table 3.5: Dimension of the steel pipe specimen

NPS designator	DN designator	Outside diameter. in (mm)	Nominal wall thickness in (mm)	Nominal weight ib/ft (kg/mm)
3/4	20	1.050 (26.7)	0.109 (2.77)	1.13 (1.68)

Type S wrought steel seamless pipe is a tubular product made without a welded seam. It is manufactured by hot working steel and if necessary by subsequently cold finishing the hot worked tubular product to produce the desired shape, dimension and properties [11].

3.7 Soil Resistivity Measurement

3.7.1 Procedures

i. Metal contacts in each end of the box pass current through the sample.
ii. Potential drop is measured across probes inserted into the soil.
iii. The resistivity is calculated using constants furnished with the particular size of soil box being used.

The engineering drawing and experiment layout for the soil resistivity measurement are shown in Figure 3.2.

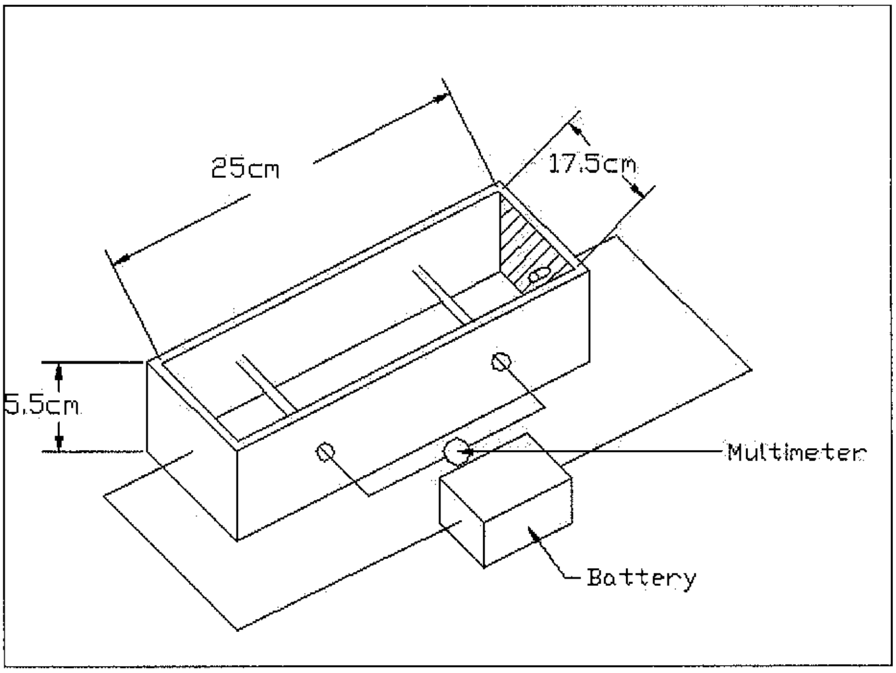


Figure 3.2: Engineering drawing showing the experimental setup of soil resistivity measurement.

By using the soil from the target area of the pipe to be buried, a battery with voltage of 12V, a multimeter, wire connections and a plastic box, a soil box was constructed as shown in Figure 3.3.

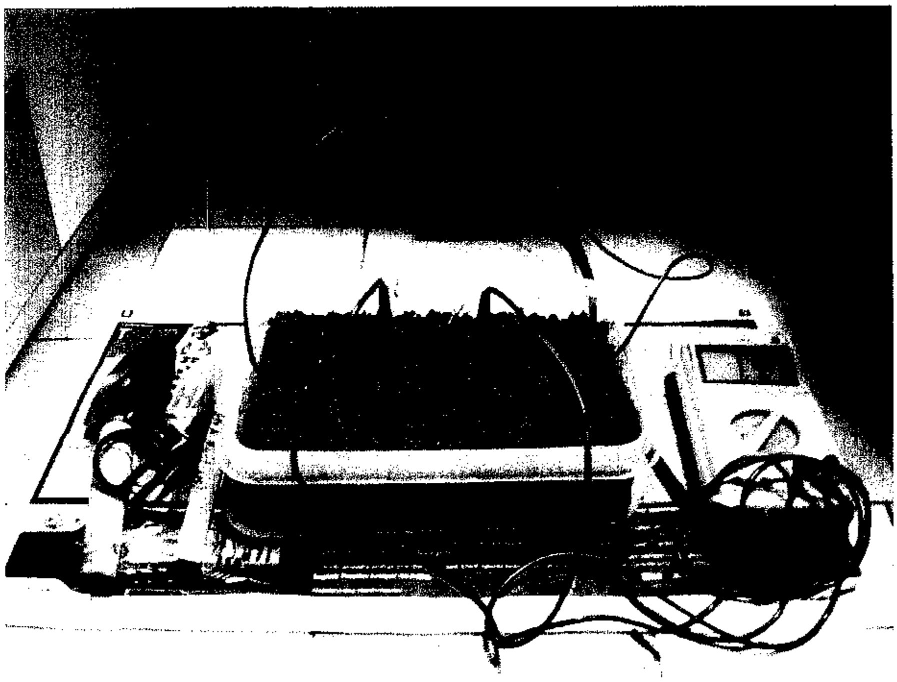


Figure 3.3: Experiment layout of soil resistivity measurement.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Results

4.1.1 Soil Resistivity Measurement

Taking 10 readings of soil resistance, the resistance of the soil (in the soil box) is recorded in Table 4.1.

Table 4.1: Resistance readings for soil using soil box method

No.	Resistance (Ohm)
1	87
2	110
3	117
4	130
5	63
6	96
7	87
8	104
9	97
10	89

Calculations

Average soil resistance = 98 Ohm

Calculating the soil resistivity

$$\rho = \frac{RA}{l} \qquad \text{(Equation 4.1)}$$

$$\rho = \frac{98\Omega \times (17.5cm \times 5.5cm)}{17cm}$$

$$\rho = 504.4 Ohm.cm$$

Where
ρ = resistivity
R = resistance of the soil (measured)
A = area of soil (dimension of soil box)
l = distance between ohmmeter pins

Precautions:

1. To minimize drying out of samples, they should be placed in plastic bags and sealed prior to test.
2. The resistance reading fluctuates, it is important to wait until the reading stabilizes before taking the measurements.

4.1.2 Sacrificial Anode Cathodic Protection System

Further studies on cathodic protection principles reveals that the protection can be conducted in two different methods:

1. Using a rectifier to supply direct current to the protected parts.
2. The use of sacrificial anode to supply required electrons.

Sacrificial anode systems are based on a metals position in the galvanic series. The galvanic series is a list of metals arranged according to there relative corrosion potentials in a specific environment.

Metals towards the top of galvanic series are more prone to corrosion attack or least noble, and the metals at the base of the series are least prone to corrosion or most noble. If connections are made with one of the metals near the top of the table with one near the bottom of the table, then the metal picked from the top of the series will corrode or be sacrificed in preference to the metal nearer the bottom of the series, hence the name sacrificial anode.

Because the galvanic system relies on the natural difference in electrical energy between the two metals, the current output levels from the anode are relatively low, depending on which type of environment (soils) or electrolytes that the anodes are placed in. This makes the galvanic type of system only suitable for soils or water which has a lower resistivity. There are some exceptions to this where sacrificial anodes are still beneficial even within a higher resistivity environment such as difficult to access structures and offshore steel jackets.

For the time being, it was found that sacrificial anode systems are more reliable than impressed current systems because there are fewer components to go wrong with this type of system and no power supply required.

Basically the sacrificial anode system comprises of:

a. Cathode, the item to be protected, steel pipes or tanks.
b. Anode, usually solid block of Magnesium, Zinc or Aluminium.
c. Connection from the sacrificial anode to the structure/parts.
d. Test facility to monitor the anode current output.
e. Isolation material between above / below ground structures.

4.1.3 Lab Scale Experiment To Test The Effectiveness Of Sacrificial Anode System

Due to several problems, full scale experiment of cathodic protection using sacrificial anode system cannot be conducted. A lab scale experiment is conducted as an alternative to test the effectiveness of this system. The detail procedure of this experiment is already highlighted in the Introduction and Methodology section. Generally this experiment uses lab scale apparatus and specimen in simulating the principle of sacrificial anode systems. The relationship between the real CP circuit and lab scale circuit are shown in Table 4.2.

Table 4.2: Relationship between Real Cathodic Protection Circuit and Lab Scale Circuit

Main elements	Real Cathodic Protection Circuit	Lab scale representatives
Electrolyte	Soil with pH 5.8 Which is acidic	Hydrochloric Acid with pH 5.8
Anode	Deep Grounbed anode with galvanic anode alloy	Anode specimen Zinc / Aluminium
Cathode	Surface of steel pipe	Steel pipe specimen

A proper setup must be constructed since in order for galvanic corrosion to occur, five requirements must be met:

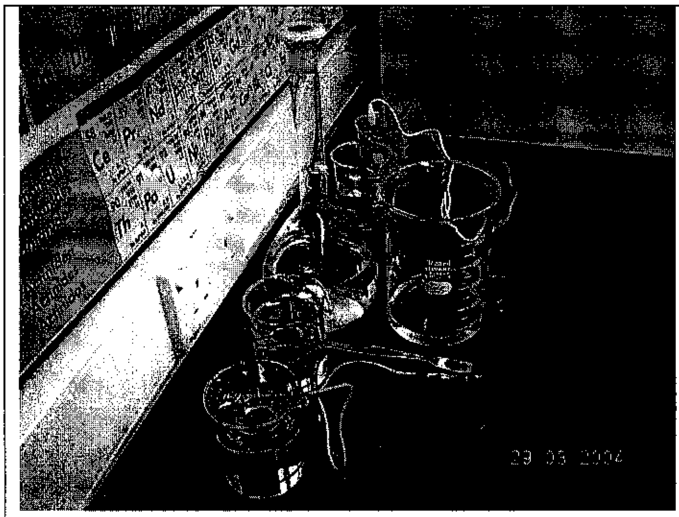
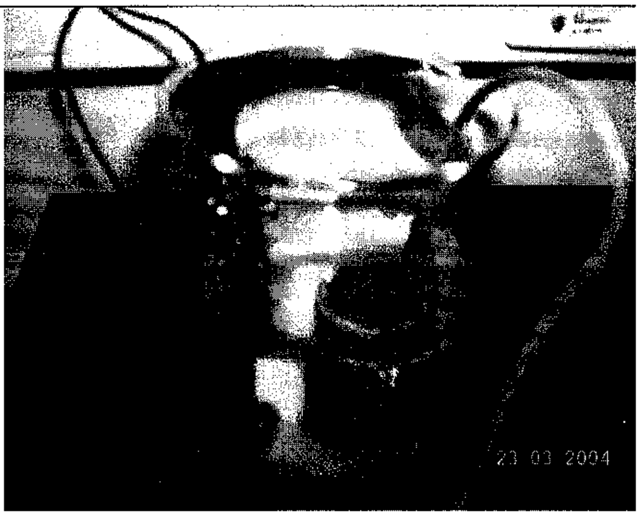
1. One metal must serve as the anode.
2. One metal must serve as the cathode.
3. There is an ionic path connecting the two electrodes.
4. There is an electrical path connecting the two electrodes.
5. There is a difference in electrochemical potential between the two electrodes

4.1.4 Lab Scale Experiment To Test The Effectiveness Of Sacrificial Anode System – Observations

4.1.4.1 Aluminium As Sacrificial Anode

By using aluminium as the sacrificial anode, the observation made on the first day and final day are summarized in Table 4.3.

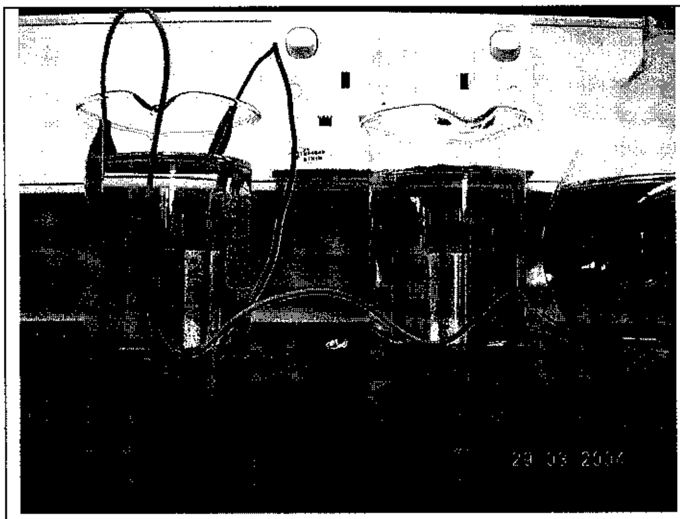
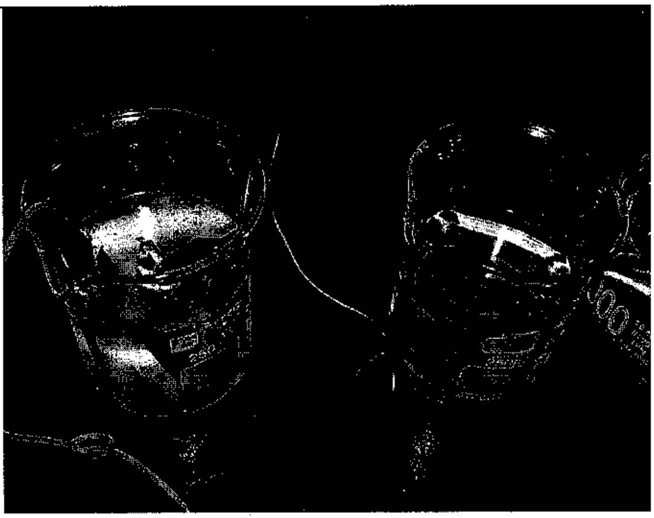
Table 4.3: Observations on the experiment using aluminium as sacrificial anode

	
Observation on first day	Observation on final day
Both specimens are still in shiny condition. Bubbles of hydrogen gas could be observed when the specimens are submerged in the acidic solution.	The unprotected specimen shows corrosion effec with white precipitation at the bottom. The protected specimen shows no corrosion effec but the anode (aluminium) turns from shiny appearance to dull surface.

4.1.4.2 Zinc As Sacrificial Anode

By using zinc as the sacrificial anode, the observation made on the first day and final day are summarized in Table 4.4.

Table 4.4: Observations on the experiment using zinc as sacrificial anode

	
Observation on first day	Observation on final day
Both specimens are still in shiny condition. Bubbles of gas could be observed when the specimens are submerged in the acidic solution.	The unprotected specimen shows a corrosion effect with the observation in the change of the solution color from clear into brownish color. The protected specimen does not show change in solutions color. Protected specimen is observed to have a white precipitation at the bottom.

4.1.5 Lab Scale Experiment To Test The Effectiveness Of Sacrificial Anode system – change in mass

4.1.5.1 Aluminium As Sacrificial Anode

The mass change of protected and unprotected steel as well as its associated sacrificial anode is recorded in two days interval (48 hours) for two weeks for each experiment. The readings for aluminium as sacrificial anode are shown in Table 4.5.

Table 4.5: The mass of specimens in HCL solution using aluminium as sacrificial anode

Date	Time elapsed (hours)	Mass		
		Protected Steel	Unprotected Steel	Anode
26/03/04	0	79.38	76.36	32.10
28/03/04	48	79.38	76.33	32.10
30/03/04	96	79.38	76.27	32.10
01/04/04	144	79.38	76.21	32.13
03/04/04	192	79.38	76.17	32.16
05/04/04	240	79.38	76.15	32.16
07/04/04	288	79.38	76.11	32.18
09/04/04	339	79.38	76.09	32.18

4.1.5.2 Zinc As Sacrificial Anode

Similar to aluminium as sacrificial anode, the mass change of protected and unprotected steel as well as its associated sacrificial anode is recorded in two days interval (48 hours). The readings for zinc as sacrificial anode are shown in Table 4.6.

Table 4.6: The mass of specimens in HCL solution using zinc as sacrificial anode

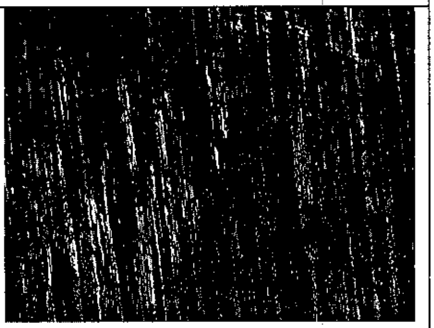
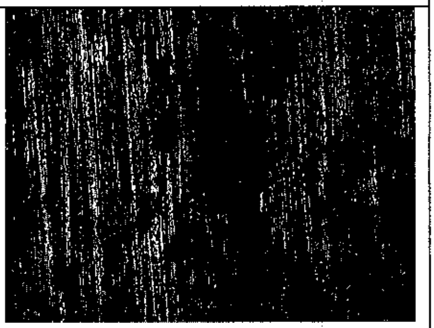
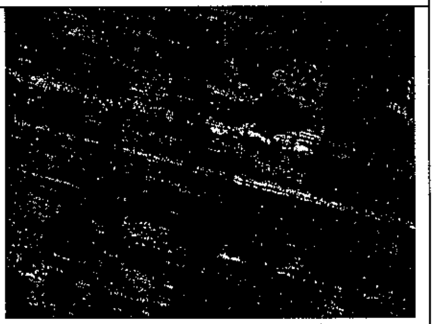
Date	Time elapsed (hours)	Mass		
		Protected Steel	Unprotected Steel	Anode
26/03/04	0	79.03	76.15	11.57
28/03/04	48	79.01	76.12	11.5
30/03/04	96	78.99	76.07	11.46
01/04/04	144	78.97	76.03	11.34
03/04/04	192	78.96	75.99	11.27
05/04/04	240	78.95	75.96	11.19
07/04/04	288	78.94	75.93	11.04
09/04/04	339	78.92	75.9	10.98

4.1.6 Lab Scale Experiment To Test The Effectiveness Of Sacrificial Anode System – Microstructure

4.1.6.1 Aluminium As Sacrificial Anode

To further enhance observations of corrosion effect on the surface of specimens, microstructure images are captured using microscopes before and after the experiment. The images for aluminium as sacrificial anode are shown in Table 4.7.

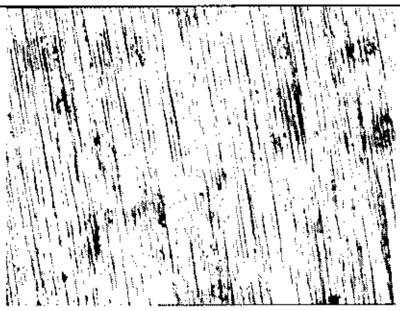
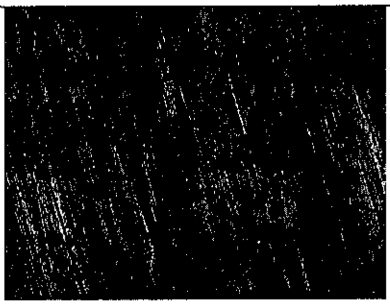
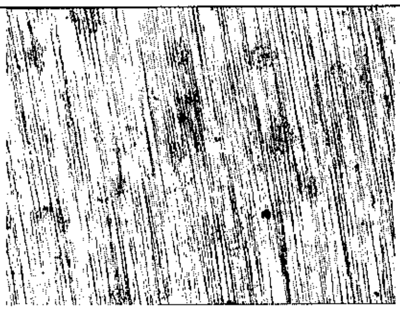
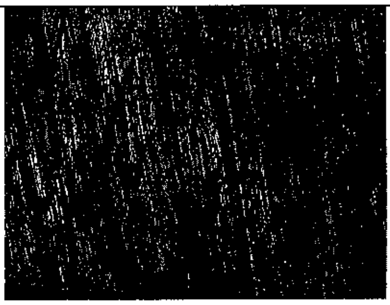
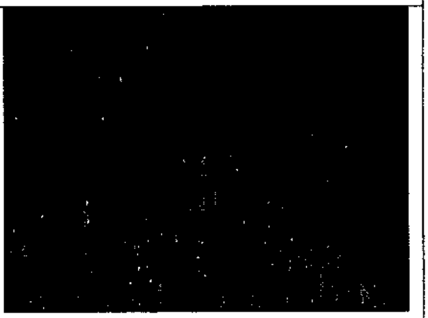
Table 4.7: The microstructure of specimens before and after corrosion process using aluminium as sacrificial anode

Item	Microstructure	
	Initial	Final
Protected Steel Pipe		
Unprotected Steel Pipe		
Anode (aluminium)		

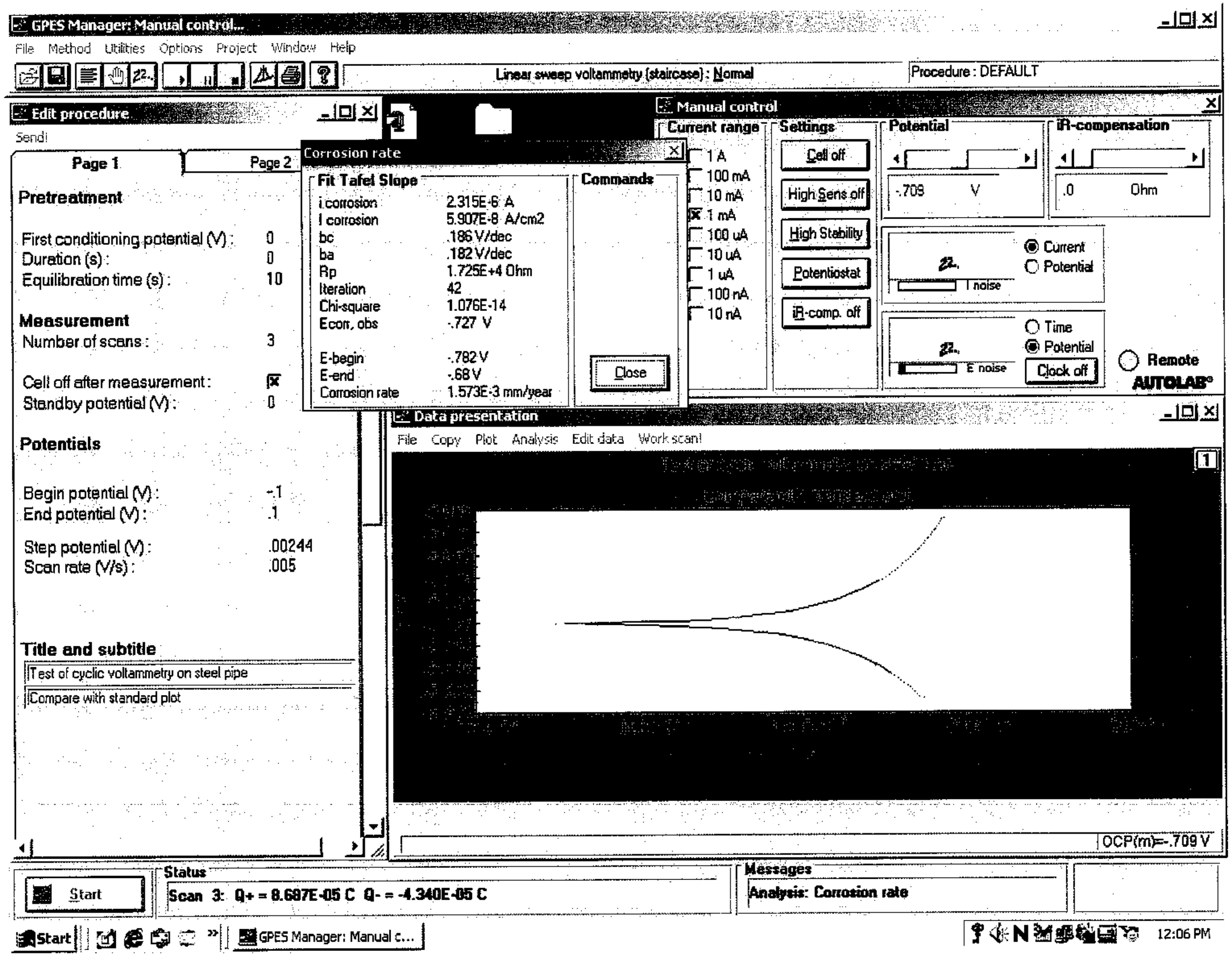
4.1.6.2 Zinc As Sacrificial Anode

The same procedure also being applied to specimens using zinc as its sacrificial anode, again to enhance observations of corrosion effect on the surface of specimens, microstructure images are captured using microscopes before and after the experiment. The images for zinc as sacrificial anode are shown in Table 4.8.

Table 4.8: The microstructure of specimens before and after corrosion process using zinc as sacrificial anode

Item	Microstructure	
	Initial	Final
Protected Steel Pipe		
Unprotected Steel Pipe		
Anode (zinc)		

4.1.7 Measurement Of Corrosion Rate By AUTOLAB Application



Linear sweep voltammetry (staircase) : Normal

Procedure : DEFAULT

Pretreatment

First conditioning potential (V) : 0
Duration (s) : 0
Equilibration time (s) : 10

Measurement

Number of scans : 3

Cell off after measurement : ☒
Standby potential (V) : 0

Potentials

Begin potential (V) : -1
End potential (V) : .1

Step potential (V) : .00244
Scan rate (V/s) : .005

Title and subtitle

Test of cyclic voltammetry on steel pipe
Compare with standard plot

Fit Tafel Slope

i corrosion	2.315E-6 A
I corrosion	5.907E-8 A/cm2
bc	.186 V/dec
ba	.182 V/dec
Rp	1.725E+4 Ohm
Iteration	42
Chi-square	1.076E-14
Econ, obs	-.727 V
E-begin	-.782 V
E-end	-.68 V
Corrosion rate	1.573E-3 mm/year

Potential: -.709 V

iR-compensation: .0 Ohm

OCP(m)=-.709 V

Scan 3: Q+ = 8.687E-05 C Q- = -4.340E-05 C

Analysis: Corrosion rate

Figure 4.1: AUTOLAB result that indicates that the corrosion rate for the pipe specimen = 1.573 x 10^{-3} mm/year

4.2 Discussion

4.2.1 Graphical Representation Of Result (mass reduction)

4.2.1.1 Aluminium As Sacrificial Anode

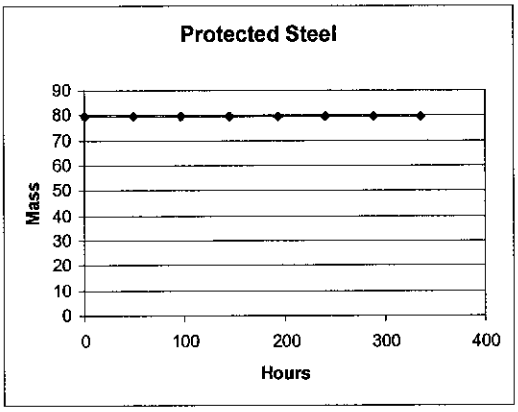


Figure 4.2: Mass versus hours for protected steel (aluminium anode) in a pH 5.8 HCL solution

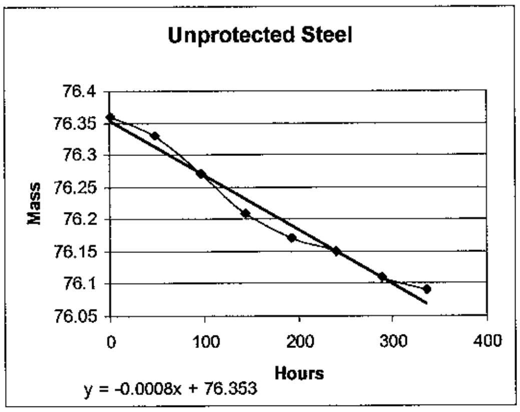


Figure 4.3: Mass versus hours for unprotected steel in a pH 5.8 HCL solution

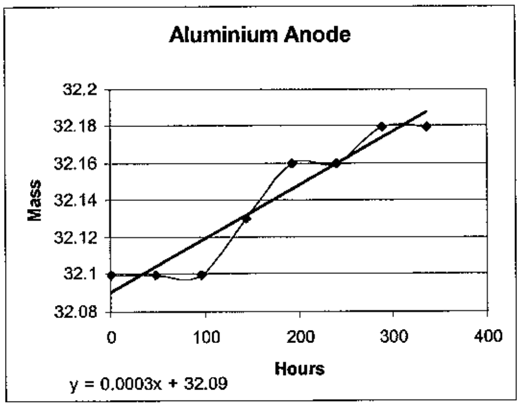


Figure 4.4: Mass versus hours for sacrificial anode (aluminium) in a pH 5.8 HCL solution

4.2.1.2 Zinc As Sacrificial Anode

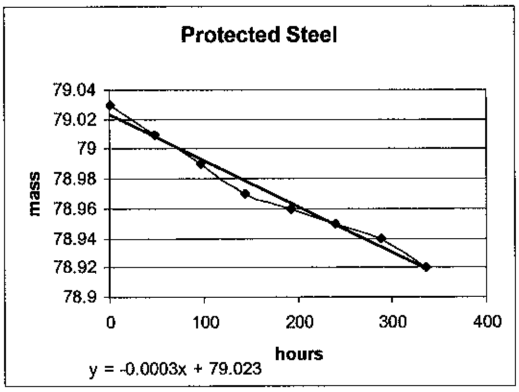


Figure 4.5: Mass versus hours for protected steel (zinc anode) in a pH 5.8 HCL solution

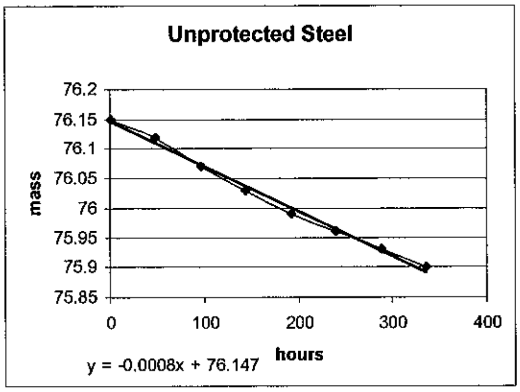


Figure 4.6: Mass versus hours for unprotected steel (control experiment) in a pH 5.8 HCL solution

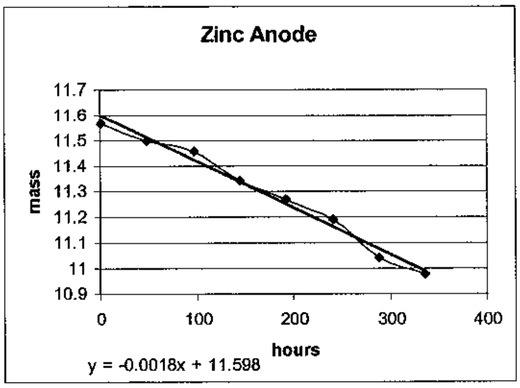


Figure 4.7: Mass versus hours for sacrificial anode (zinc) in a pH 5.8 HCL solution

4.2.2 Reactions At Anode And Cathode

The chemical reactions for the protected steel and its associated sacrificial anode is summarized in Figure 4.8 using steel cathode and zinc anode in Hydrochloric acid electrolyte as an example.

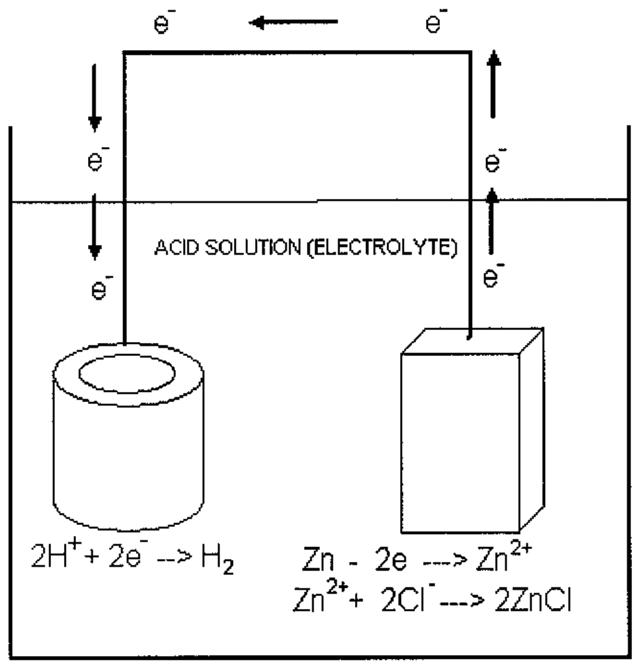


Figure 4.8: chemical reactions that occur at both anode and cathode for zinc protected steel pipe.

From the figure above, it could be observed the formation of areas where cationic dissolution is favored (due to relatively high cationic activity) and areas where electron consumption must be undertaken to allow the corrosion process to proceed (areas of relatively low cationic activity). The former sites are called anodic sites and the latter cathodic sites. In metal both sites must co-exist, though they must change in location periodically due to build-up of corrosion product.

For Aluminium protected steel pipe in an HCL solution of pH 5.8, the following reactions are found out to take place.

At the anode

$$Al - 3e^- \rightarrow Al^{3+}$$

$$Al^{3+} + 3Cl^- \rightarrow AlCl_3$$

This reaction explains the presence of white precipitate at the bottom of the beaker which is basically Aluminium Chloride.

At the cathode

$$2H^+ + 2e^- \rightarrow H_2$$

This explains the presence of bubbles which emerge when the specimen is submerged into the acidic solution (hydrogen gas).

For Zinc protected steel pipe in an HCL solution of pH 5.8, the following reactions are found out to take place:

At the anode

$$Zn - 2e^- \rightarrow Zn^{2+}$$

$$Zn^{2+} + 2Cl^- \rightarrow 2ZnCl$$

This reaction explains the presence of white precipitate at the bottom of the beaker which is basically Zinc chloride.

At the cathode

$$2H^+ + 2e^- \rightarrow H_2$$

This explains the presence of bubbles which emerge when the specimen is submerged into the acidic solution (hydrogen gas).

For an unprotected steel pipe in an HCL solution of pH 5.8, the following reactions are found out to take place

At the anode region

$$Fe - 2e^- \rightarrow Fe^{2+}$$

$$Fe^{2+} + 2Cl^- \rightarrow 2FeCl$$

The Ferum (Fe) ion itself will lose electron and reacts with negative chloride ion to form Ferum chloride. The ionization of Ferum ions is the main objective of cathodic protection.

At the cathode region

$$2H^+ + 2e^- \rightarrow H_2$$

Hydrogen gas is undesirable though sometimes as unavoidable cathodic product as it can produce hydrogen embrittlement in high strength steels and weldments, which give rise to safety problems.

4.2.3 Advantages And Disadvantages Of Aluminium And Zinc As A Sacrificial Anode.

Aluminium is located just below magnesium in the galvanic series which gives it almost the same advantages and disadvantages of magnesium. It delivers high current output. Aluminium anodes are not economical sources of current in soils of high resistivity: their usage is limited almost entirely to soils of less than 3000 ohm-cm. The passivation effect of aluminium anode also limits the usage of aluminium in soils. The passivation effect occurs when the aluminium oxide does not fall off the aluminium surface, becoming a protection layer for the aluminium thus preventing further corrosion. This is not feasible since in cathodic protection, the anode must always corrode to protect the cathode.

The natural potential between zinc and steel is lower than that between aluminium and steel. Consequently, other things being equal, the current output of a zinc anode will be lower than that of a magnesium anode of the same size; this is a disadvantage in a higher resistivity soil.

Low current output for zinc anode made its efficiency higher, so it is possible in many cases to install zinc anodes with a projected life of 20 to 40 years. In some other circumstances, the low driving potential of zinc with respect to steel can be a disadvantage. If malfunction such as coating failure or resistivity changes, the current output of the zinc anodes will vary over wide range, with very little shift in the potential of the protected structure.

4.2.4 Industry Solution In Sacrificial Anode Cathodic Protection System – Magnesium Anode

The principal advantage of magnesium anodes, as compared to other cathodic protection system such as using rectifiers, is that the current may be distributed much more readily, since it comes in small packages. There is always a certain amount of over-protection of a pipe line near the drain point. This is called wasted current and system must be developed so that each part of the pipe receives just what it needs. A properly applied magnesium anodes can protect a line with less current than a system of rectifiers. But current from rectifiers costs less per ampere than that from magnesium, so it is not always true that a pipeline can be protected for less cost with anodes

Same as Aluminium, Magnesium anodes are not economical sources of current in soils of high resistivity (limited to soils of less than 3000ohm-cm). It is important to note that cathodic protection will not be sufficient to be used solely by itself; it must be paired with efficient coating system to achieve full protection.

The field of application of magnesium anodes is in the protection of bare lines, of isolated structures, as auxiliary protection, and in the protection of some coated lines, provided the soil conditions are suitable for their use.

4.2.5 Lab Scale Experiment Of Sacrificial Anode Cathodic Protection System – Relation With The Real CP System.

Basically this experiment is conducted to justify the theory that metal with higher reactivity will protect other metal with lower reactivity if both metals are connected in a corrosive environment with the presence of electrolyte. The experiment layout is shown in Figure 4.9.

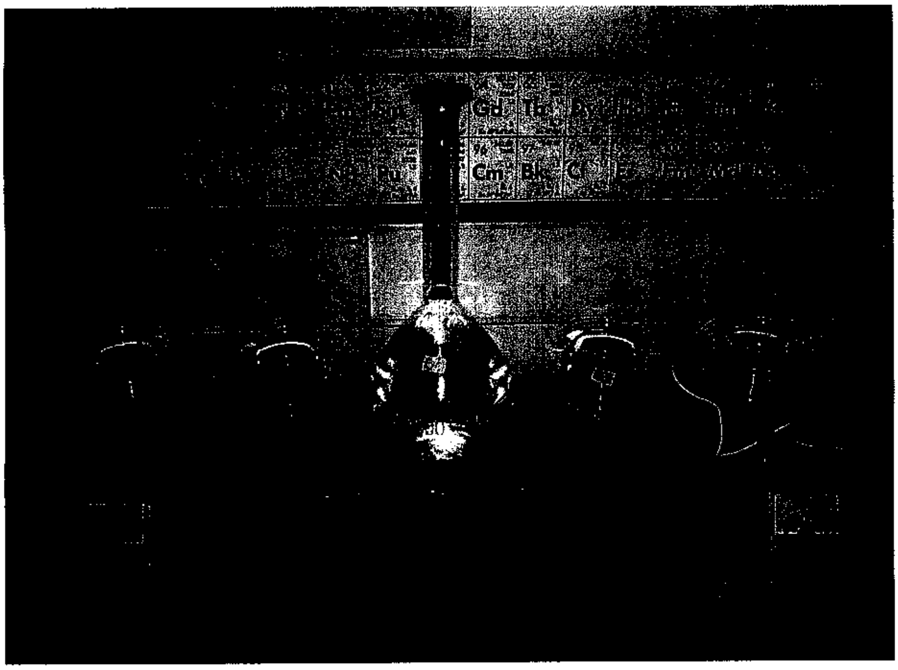


Figure 4.9: The laboratory scale sacrificial anode cathodic protection system.

The experiment is conducted in such a way to represent the actual environment of corrosion in soil. Two different type of sacrificial anode are used aluminium and zinc, both with different potential relative to steel. The pipe sample is a 1 inch steel pipe, SIRIM certified with the cert no of PS006502. The original sample has a protective coating with prevent the pipe from corroding; grinding work is done to remove the protective layer in order to measure the effect of cathodic protection alone in protecting metal.

The electrolyte is prepared in such a way to represent the actual pH of the environment. Since this experiment requires accelerated corrosion in order to meet the time restrictions, a solution of HCL acid is used with pH 5.8 (soil pH).

To justify the result, each experiment is paired with a control experiment, which is a pipe submerged in an acidic solution without protection. After certain duration, both specimens are weighted to measure the decrease in mass. Graphs of mass reduction against time are plotted for each specimen to find its corrosion rate.

For protected steel with aluminium anode, no change in mass is detected for the total of 336 hours of the experiment; this clearly shows the effectiveness of higher potential anode such as aluminium in protecting steel. This is further justified by the decrease of mass of unprotected steel by 0.0008 grams/hour and the continuous increase of aluminium anode by 0.0003 grams/hour. The effect of passivation could already be observed at this phase where the surface of the aluminium is covered by dark oxides.

Using lower potential anode such as zinc, the protection is less effective since there is a small reduction of the protected steel pipe mass by 0.0003 grams/hour. Same reduction of mass could be observed on the control experiment (decrease of mass by 0.0008 grams/hour). Unlike aluminium, zinc anode does not show passivation effect where there is significant reduction of anode mass by 0.0018 grams/hour.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This project is being conducted with the goal of studying the principles of cathodic protection of underground pipe and recommends the optimum ways to cathodically protect metal parts. From this report, the bases of the project are completed and all objectives have been met.

The first objective which is to study the principles of cathodic protection of underground pipe has been completed in the first half of the project where researches are conducted via reference books, journals and also via the internet to gain in depth knowledge about cathodic protection. This is important since this knowledge would help in accomplishing other objectives.

The second objective is to construct a laboratory experiment to test the effectiveness of cathodic protection of a steel pipe and to compare it with an unprotected one. Instead of building a full scale size of sacrificial anode cathodic protection system, the author has constructed a lab scale of this experiment for easy monitoring and comparable results. The experiment was a successful one since it clearly shows the positive effect of cathodically protecting steel pipe in a corrosive environment. The corrosion rate of the protected pipe is greatly reduced compared to the unprotected one. Comparisons between different anodes are also being made to show the difference in effect of different potential. As a bonus, the author has observed the passivation effect which explains why not all anodes are suitable for usage in cathodic protection principle.

Comparison between the conducted experiment and industrial practice gives clearer idea on how this experiment relates to the current industry. A further study on today's practice in cathodic protection shows various methods in order to increase the efficiency on this type of protection.

5.2 Recommendation

5.2.1 Improving Experimental Result

For future work it is recommended that a full scale experiment representing actual corrosion environment is conducted to obtain better observation and results on the cathodic protection. Simulation of actual buried pipe in such an environment could be conducted in the corrosion chamber to accelerate the process. For better comparison, it is recommended that the experiment is conducted using variations of anode from industry such as magnesium alloys in order to observe its real effectiveness. Comparisons can also be made with another system using rectifier as electron source instead of metal anode to show another variation in cathodes protection as used in industry currently.

5.2.2 Considerations In Constructing CP System In Industry

A lot of variables must be considered in constructing an efficient CP system in industry. Great combination of these factors would ensure efficient and reliable cathodic protections system. Among the factors are:

Anode

The most obvious part of the corrosion cell is the anode. This is the location where corrosion occurs. The anode is the point in a corrosion cell where electricity is passed by chemical means from the surface of the metal to the electrolyte. This chemical reaction is an oxidation reaction, which is characterized by the metal loosing an electron and combining with another element, usually oxygen. In the case of steel, the resulting material is iron oxide (rust).

Cathode

The second part of the corrosion cell is the cathode. This is the location where protection occurs. The cathode is the point in a corrosion cell where electricity is passed by chemical means from the electrolyte to the surface of the metal. This chemical reaction is a reduction reaction, which is characterized by the metal passing electrons to the electrolyte.

Anode/Cathode Relationship

An electrode becomes either an anode or a cathode in an electrochemical corrosion cell depending upon its electrical potential compared to the other electrode. This electrical potential difference is the electromotive force of the cell and is the voltage difference between the anode and the cathode. The electrode which is more electrically active, or more negative in voltage, undergoes the corrosion, so by definition is the anode. The electrode which is more noble (less negative in potential), passes electrons to the electrolyte (reduction reactions) and by definition is the cathode and does not undergo corrosion (oxidation reactions). As previously discussed, there are four distinct parts to the electrochemical corrosion cell, all four parts must be present for a complete circuit to exist and for current to flow (corrosion to occur).

Electrolyte

The third part of the corrosion cell is the electrolyte. The electrolyte is the location where ions flow. The electrolyte is any material in contact with both the anode and the cathode which will allow ions to migrate. The electrolyte is the part of a corrosion cell which allows oxidation and reduction reactions to occur. The electrolyte includes the source of elements or atoms which are required for ion transfer to and from the metal electrodes (anode and cathode).

Metallic Path

The fourth part of the corrosion cell is the metallic path. The metallic path completes the circuit and allows the electrons to flow. The metallic path is any metal which contacts both the anode and the cathode and allows electrons to flow. This electron flow must be present for electrochemical corrosion to occur. In the case of a tank or pipeline, this can be the tank or pipe itself, or it can be a metallic bond to different metallic structure.

Electrical Effects On The Rate Of Corrosion

Any factor which affects the amount of current flowing in a circuit will affect the rate of the electrical portion of the electrochemical reaction (corrosion). Following is a description and example of the factors affecting the rate of the electrical portion of corrosion.

Potential Difference

The potential difference between the anode and the cathode is electromotive force and can be measured as voltage. The greater this difference, or voltage, the greater the potential of corrosion. The voltage is directly proportional to the current, and therefore the corrosion, in an electrochemical cell. If the voltage is doubled, and all other factors remain the same, the amount of corrosion doubles.

Resistivity Of The Electrolyte

The resistivity of the electrolyte is normally a significant factor in determining the rate of corrosion. This is an uncontrollable characteristic of the soil or water (the electrolyte). The definition of an electrolyte is a material which will allow ions to migrate, and the resistivity is the rate at which it allows ions to migrate. Resistivity is the inverse of the conductivity and is measured in ohm-centimeters. Resistivity is inversely proportional to current, and therefore to corrosion, in an electrochemical cell. If the resistivity is doubled, and all other factors remain the same, the amount of corrosion is cut in half.

Contact Resistance

The contact resistance of the anode to electrolyte and of the cathode to electrolyte has the same effect as resistivity, since it is a measure of resistance. The lower the resistance, the greater the current (corrosion). If the contact resistance of the anode or the cathode is doubled, and all other factors remain the same, the amount of corrosion is cut in half. Note that if the contact resistance of both the anode and the cathode is doubled, the amount of corrosion is only one-fourth of its original value.

Coating Of The Structure

Coating of the structure normally raises the contact resistance of the anode and the cathode since most coatings are dielectric in nature (nonconductive).

Polarization Of The Structure

Polarization is the change of the electrode potential as a result of the electrochemical current flow and usually results in the formation of a film on the electrode surface called a polarization film. Polarization film consists partly of a thin film of hydrogen on the cathode surface. This polarization film and other changes have beneficial effects at the cathode. The layer of hydrogen acts as an additional coating, water is driven away from the surface of the cathode, ion concentration in the electrolyte is reduced, the contact resistance of the electrode to electrolyte is raised, and essentially, corrosion cell current no longer flows or is reduced to a small fraction of its previous value.

Amount Of Current Flow

The amount of current flow directly influences the rate of corrosion. Corrosion can be determined from the amount of current flow. Each metal has definite characteristics in the number of electrons given up in the oxidation process and the number of atoms in a kilogram (pound) of the metal. This can, therefore, be translated to kilograms (pounds) per amp. The normal unit of measure encompasses a one year period -- kilograms (pounds) per amp-year.

Area Relationships

The relative size of the anodic area and the cathodic area can greatly affect the rate of corrosion, especially under stray current conditions. When the anodic area is very small, and the cathodic area is large, the corrosion is concentrated and generally becomes more severe. Under stray current conditions, this size relationship is extremely critical. The current density at the cathode under stray current conditions can be extremely high, resulting in failure of the structure in an extremely short period of time.

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APPENDIX 3-1 Gantt Chart for First Semester Final Year Project

No.	Detail	WEEK															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	SW	EW
1	Selection of Project Topic		■														
2	Preliminary Research Work			■	■	■											
	- Introduction																
	- Objectives																
	- List of references / literatures																
	- Project Planning																
3	Submission of Preliminary Report					● 18/8											
4	Literature Review on Sacrificial Anode Cathodic Protection System					■	■	■	■	■							
5	Submission of Progress Report									● 22/9							
6	Experiment In Determining Soil Resistivity									■	■	■	■	■			
7	Submission of Interim Report Final Draft													● 20/10			
8	Oral Presentation															■	
9	Submission of Interim Report																● 21/11

APPENDIX 3-2 Gantt Chart for second Semester Final Year Project

No.	Detail	WEEK															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	SW	EW
1	Apparatus and Specimen Preparation For Experiment	■	■	■	■	■											
2	Submission of Progress Report 1					● 16/2											
3	Lab Scale Experiment Of Cathodic Protection Using Aluminium And Zinc As Sacrificial Anode					■	■	■	■	■							
4	Submission of Progress Report 2									● 22/3							
5	Result Analysis Of The Experiment Of Cathodic Protection Using Aluminium And Zinc As Sacrificial Anode									■	■	■	■	■			
6	Submission of Dissertation Final Draft													● 23/4			
7	Oral Presentation															● 30/4	
8	Submission of Project Dissertation																● 31/5