EFFECTIVENESS OF IMPRESSED CURRENT CATHODIC PROTECTION SYSTEM ON UNDERGROUND STEEL ENGEN REFINERY TRANSFER LINES SYSTEM

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ABSTRACT

This study investigated to determine the effectiveness of impressed current cathodic protection (ICCP) on protecting Engen underground steel transfer lines from corrosion. These lines have a history of leaks aggravated by stray currents from a direct current (DC) traction system. The main challenge facing the organisation under study is to find a solution to this situation. Different types of field surveys and simulations were performed, such as pipe-to-electrolyte or soil “ON” spot potential, DC stray current, close interval potential (CIPS), direct current voltage gradient (DCVG), transformer rectifier unit (TRU) performance, soil resistivity, alternating current (AC) interference, anode ground bed (AGB) performance, instant OFF pipe-to-soil potential. Surveys were categorised into two groups. These were baseline and post-surveys. The main objective was to check the difference or deviation from previous results. Baseline surveys were done before upgrading the anode ground beds at Swamp, Checkers, and Travancore TRU locations. Post-surveys were performed after the upgrade of anode ground beds (AGB’s) on the above-mentioned locations to validate the reliability of the anode upgrades. Some of the cathodic protection (CP) polarisation criteria standards such as NACE 0169, TM0497, TM0102, RP0285, PDO-65-12, 0SAES-X-400, ADNOC, ISO 15589-1, API were used as a reference during the field survey and simulation data collection, data analysis, conclusions and recommendations. The underground pipelines that have aging coating will show and will demand a high cathodic protection current to comply with CP underground structure polarisation criteria. By performing CIPS, DCVG, DC stray current, anode ground bed performance and instant “OFF” pipe-to-soil polarisation surveys, it was possible to gauge the transfer lines’ coating status, anode ground bed status, defect locations and entry points of stray current. These surveys also contributed to making effective conclusions and recommendations for the organisation to have a safe, reliable Engen steel underground transfer lines system.

Keywords: Impressed Current, Cathodic Protection System, Underground Steel, Anodes, Transformer Rectifier Unit, Engen Refinery, Transferlines, Anode Ground Bed, Close Interval Potential, Polarisation Criteria Standards, Pipe to Soil Potential, Direct Current Voltage Gradient, Coupon.

DEDICATION

I dedicate this dissertation to my Creator who has given me an opportunity to live, and the strength and all the resources throughout this journey. I also dedicate this work to my parents, Mrs Nkosingiphile and Mr Lindinkosi Dube, for their sacrifices to provide me with an excellent opportunity to study. Furthermore, my wife Mrs Penelope Dube, who has been a reliable and robust pillar to fulfil my dream. My young daughter, Miss Minenhle Dube, who is always encouraging me by saying “Daddy, Rome was not built in a day”.

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A quote by Robert Conklin which is always close to my heart says, “if you make the unconditional commitment to reach your most important goals, if the strength of your decision is sufficient, you will find the way and the power to achieve your goals”

I would like to acknowledge and appreciate Mr. Nkosinathi Chonco (Engen Electrical Manager) for his support in approving my financial documents requesting Engen Management to provide an Author bursary for the study and getting a permit to utilise Engen asserts to conduct the study. Furthermore, I would also like to thank Engen Management for approving the bursary immediately.

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LIST OF ABBREVIATIONS

AC	Alternating Current
AGB	Anode Ground Bed
CFR	Code of Federal Regulations
CIPS	Close Interval Potential Survey
CP	Cathodic Protection
CSE	Copper Sulphate Electrode
DC	Direct Current
DCVG	Direct Current Voltage Gradient
DSR	Direct Soil Resistivity
DUT	Durban University of Technology
Em	Mix potential
Epa	Polarised Anode Potential
Epc	Polarised Potential of the Cathode
ICCP	Impressed Current Cathodic Protection
IF	Insulation Flange
Irr	Corrosion Current
mA	Milli Ampere
mV	Millivolt
NACE	National Association of Corrosion Engineers
SHE	Standard Hydrogen Electrode
SSC	Silver- Silver Chloride Electrode

TRU	Transformer Rectifier Unit
V_R	Voltage Drop

LIST OF SYMOBLS

Ω	Ohm
AgCl	silver chloride
m^2	meter squared
%	percentage
$CuSO_4$	copper sulphate

Chapter 1: Introduction and Overview

1.1 Introduction

Underground pipeline leaks in most cases result from mechanical damage, coating defects, and stray currents from a direct current (DC) traction system. The stray current problem areas happen where a portion of the traction current returns to the substation via earth rather than through the return rail, which results in corrosion [1].

Mechanical damage during installation, pipeline coating defects or an aging pipe coating can lead to exposed protected structure to have moisture ingress, electrochemical reaction, oxygen and other corroding sorts. This can eventually cause external corrosion on the buried steel that in mechanical failure and causes pipe leaks. A supplementary means of protection is needed to ensure long-term reliability of the underground steel pipelines.

In many countries, generally protected from corrosion by a combination of coating and a cathodic protection system as specified in the Code of Federal Regulations (CFR) after July 31, 1971[2]. Too many accidents are caused by pipe corrosion every year. The corrosion rate is mainly determined by cathodic reaction [3].

According to Zhengfeng et al, buried steel pipelines are commonly prevented from external corrosion by both application of coatings and cathodic protection. Furthermore, impressed current cathodic protection can complete the protection system by preventing corrosion of the steel surface at defects, which would develop on the coatings through the aging process [4].

Christodoulou et al. stated that impressed current cathodic protection is a technique utilised since the 1970s and arrest corrosion, induce and sustain steel passivity. Furthermore, the main principle of cathodic protection (CP) is to apply an impressed current to induce negative steel polarisation. This means it drives the steel potential to not less than -850mV (CSE) with respect to surrounding earth. Under this condition, corrosion processes will not occur [1].

To ensure reliable and safe operation of underground steel pipelines, impressed current cathodic protection (ICCP) is the most reliable technique for corrosion prevention of steel pipelines. Effectiveness may be reduced at coating defects due to coating [5].

ICCP works more effectively in reducing or preventing the corrosion of any metal or alloy exposed to an aggressive environment. It extends the service life of thousands of kilometres of buried steel pipelines, offshore oil drilling structures, liquefied petroleum gas bullets, etc. To design an effective ICCP system, knowledge of surface current density and electrochemical potential surface is necessary [6].

Impressed current cathodic protection effectiveness may be reduced at corrosion pits and cracks. Field experiences have contributed to finding a significant number of corrosion defects on the external surface of cathodically protected pipelines after several years of service and proactively repaired them. According to Cheng et al., in the absence of AC interference or at a low AC density, i.e. 20A/m^2 a CP potential of -950mV (CSE) provides full protection over the steel [6].

1.2 Problem statement

Petroleum Refineries are currently facing challenges of the external corrosion rate and leaks on their underground steel piping system. Another concern is the negative effects of the stray currents, which create corrosion and leaks [7].

Underground steel pipeline transportation is the most means of transporting oil, gas and other petrochemical products. It is cost effective, relatively reliable, but corrosion is a significant for its safe operation. Furthermore, industry reports reveal that external corrosion accounts for approximately 40% of structural integrity problems in the oil and gas transmission pipelines network [8].

Underground external steel pipeline corrosion in most cases is caused by moisture, penetrated via coating defects, aeration, presence of stray currents and etc [7].

1.3 Engen Refinery challenge

Engen Refinery has underground steel transfer lines installed in the early 1960s. At great expense, some of transfer line sections have been replaced. There is concern over a trend of transfer lines’ leaks due to underground corrosion. These transfer lines are installed in highly populated areas and share the servitude with other organisations’ underground utilities. The leaks can lead to a major safety impact on people, equipment, and environment. Engen is well aware that this affects their reputation.

Excavating the entire length of the pipeline for inspection, repairs and approval from other stakeholders is too costly. Sections of the transfer lines have CP systems. The CP system has reached the end of its life based on analysis of the reports on the tested results.

To determine the effectiveness of a CP system as an effective supplementary technique in protecting transfer lines against underground corrosion. In addition, the intention is to protect these transfer lines against stray current from the DC traction system and as a long-term solution to this challenge the organisation is currently facing.

1.4 Research questions

The main objective of this investigation was to find resolutions to the following questions:

- What are the underground factors that affect the underground pipelines’ coating?
- What improvement will ICCP have to overcome these factors to avoid or control stray current, minimise corrosion, reduce future leaks, and prolong pipelines’ lifespan?
- How does cost of replacing the pipelines compare to the cost of an ICCP system installation?

This research sought to find an effective solution by the based of underground pipelines to prevent external corrosion.

This investigation will contribute to catastrophic transfer line failures. It will assist in proactively identifying anodic areas and have a roadmap for planning transfer line repairs or replacement. Positively contribute to unplanned outages and minimise external corrosion of transfer lines. In addition, it should in maintenance costs and avoid damaging the reputation of the organisation.

1.5 Hypotheses

The effectiveness of the impressed cathodic protection system to protect underground pipeline system can be determined by performing pipe-to-soil potential survey, DC stray current survey, close interval potential survey, direct current voltage gradient survey, testing efficiency of transformer rectifier unit, testing integrity of transfer lines' isolation flanges, soil resistivity survey, AC interference survey, anode ground bed performance survey and cathodic protection system structure polarisation compliance to NACE standards by conducting simulation using external steel coupons.

To ensure validation and reliability of the survey results, calibrated and recommended testing instruments had to be used. In addition, all data had to be carefully recorded and catagorised.

1.6 Dissertation structure

The investigation was structured in the following manner:

Chapter 1: Introduction and Overview

The content of this chapter focuses on the organisation's challenge or problem statement, study objectives, study focus, history of underground pipelines corrosion, questions and hypotheses.

Chapter 2: Literature Review

The chapter presents reviews of the published theory and research that supports cathodic protection from different sources relevant to this study, including factors affecting underground pipelines' corrosion, basic electrochemistry, nature of corrosion, polarisation of underground structure requirements, relevant cathodic protection criteria, factors affecting polarisation, cathodic protection concept, relevant field measurements, and simulations.

Chapter 3: Research Design and Methodology

This chapter focuses on different data collection and analysis techniques that were implemented and evaluated to be the most suitable for this type of study.

Chapter 4: Results and Analysis

This chapter provides recorded data and an analysis of the research on visual inspection, field simulation and testing.

Chapter 5: Conclusion and Recommendations

This chapter gives an overview of the conclusion and recommendations based on the findings during the field surveys and simulations.

All as a list of CP standards and a recommended schedule is attached as appendices.

Chapter 2: Literature Review

2.1 Introduction

Engen Refinery was built in 1954 and is based in Durban, South Africa. It comprises eight products transfer lines pipelines. The cathodic protection (CP) system for the transfer lines installed from Engen Refinery to Engen Island View sites is known as common cathode. It comprises three transformer rectifier units directly connected to the Engen transfer lines.

This chapter deals with the theoretical background based on different sources reviewed by the researcher and relevant to this study.

Figure 2.1: Engen transfer lines' routes along Tara Road, Durban

2.2 Basic electrochemistry

Corrosion and cathodic protection involve an electrochemistry process. Cathodic protection and corrosion involve electrochemistry related with a charge transfer in aqueous environments [9].

This situation is based on whether there is an excess of hydrogen (H^+) or hydrogen hydroxide (OH^-) ions. Ions are gaining or losing electrons in electrically charged a charge on an atom is known as its valence. An atom gaining extra electrons is known as an anion. It is negatively charged because the number of electrons is more than the number of protons. The loss of electrons produces a positively charged ion called a cation.

A medium is known to be acidic when there is an excess of H^+ ions. Quality of an acid is a measure of hydrogen ion concentration in an aqueous solution and is arranged according to the pH scale. pH is the negative logarithm to the base 10 of the hydrogen ion concentration

$pH = -\log(H^+)$ [10]

Based on many metals, the rate of corrosion increases substantially below a pH of about 4. Between 4 and 8, corrosion rate is independent of pH. Above 8, the environment becomes passive and corrosion rates tend to decrease. Figure 2.2 illustrate the effect pH on (a) steel, and (b) aluminium and lead.

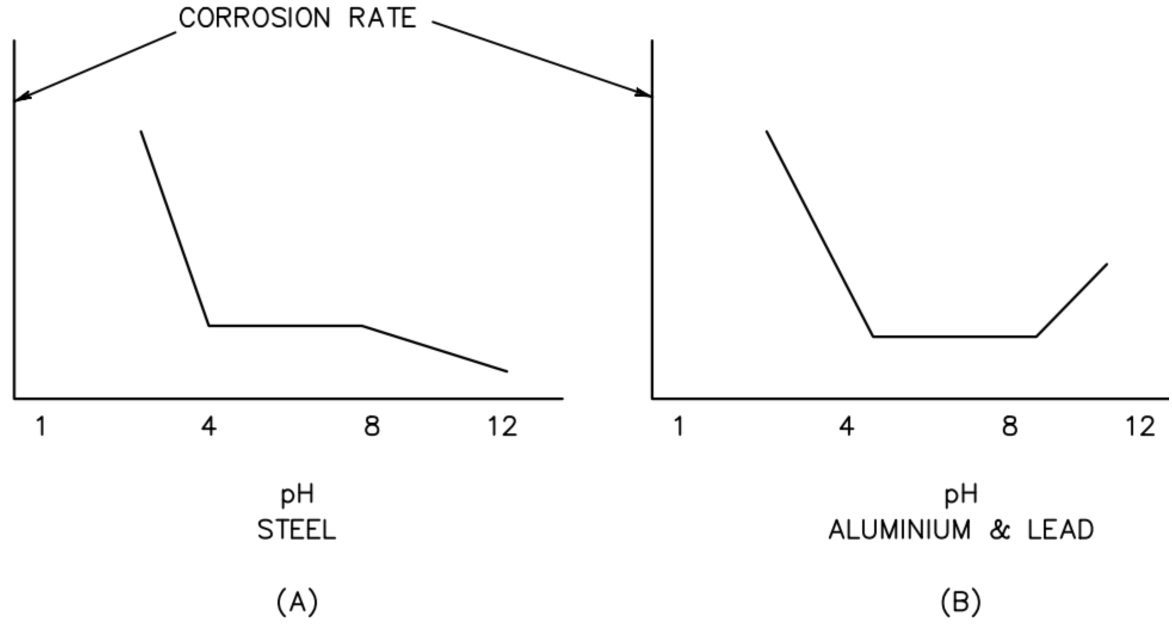


Figure 2.2: Effect of pH on the rate of corrosion [10]

The pH becomes more alkaline around the environment of the cathodic protected structure due to the production of ions or removal of hydrogen ions [11].

2.2.1 Cause of metal to corrode

The force that makes metals corrode is a natural consequence of their temporary existence in the metallic form.

The more reactive a metal is with its environment, the more energy change from its natural state to the metallic form. It is relatively high for metals such as magnesium, aluminium and iron and relatively low for copper, silver and gold [12].

2.2.2 Corrosion reaction

The dissolution of the metal is electrochemical. It is a chemical reaction accompanied by the passage of an electric current [13].

For corrosion to occur, all of the following conditions must be present:

- There must be an anode and a cathode.
- There must be a potential difference between the anode and the cathode.
- There must be a metallic path connecting the anode and the cathode.
- There must be a conducting electrolyte surrounding both the anode and the cathode.
- The anode is the area at which oxidation or corrosion occurs where the current leaves the metal to enter the electrolyte.
- The cathode is the area reduction or negligible corrosion occurs where the current leaves the electrolyte to enter the metal.
- The electrolyte is a solution in which the conduction of electric current occurs by the passage of dissolved ions.

An electric current will flow and metal will be consumed at the anode, i.e. the anode corrodes as shown on Figure 2.3

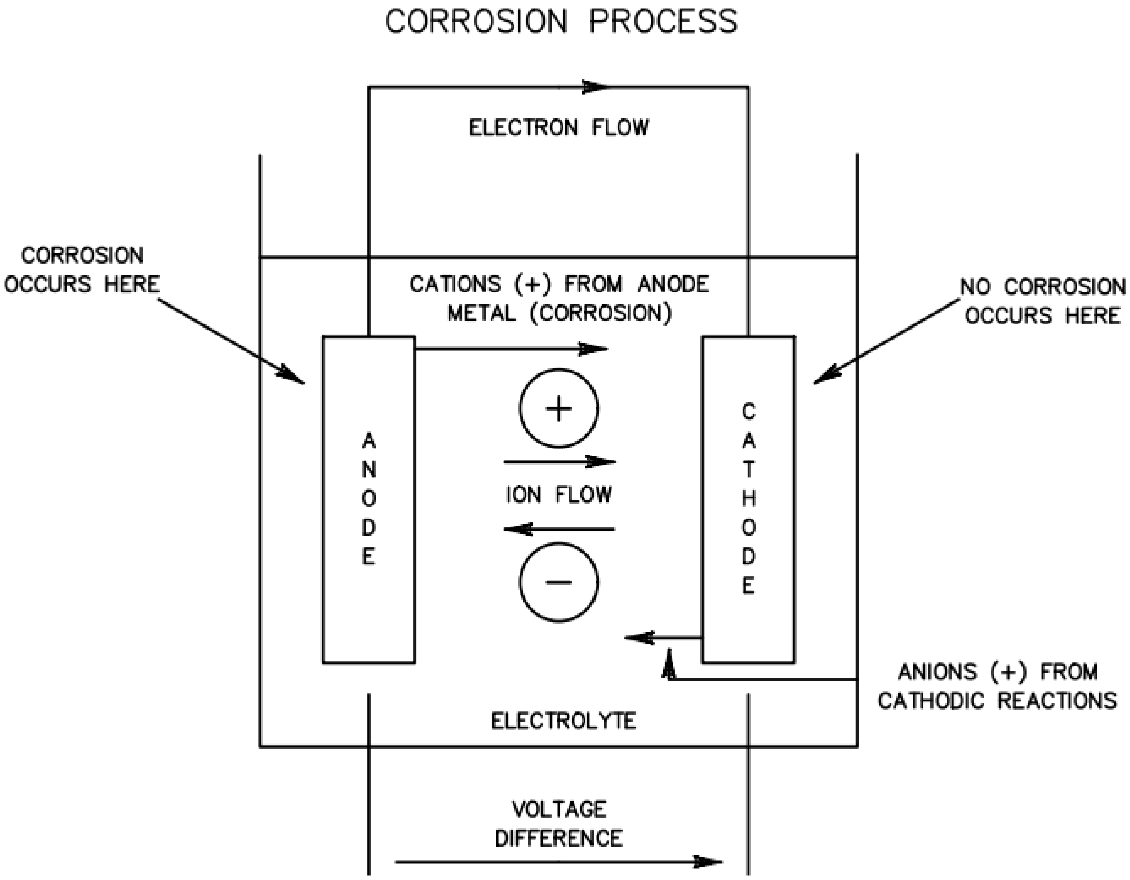


Figure 2.3: Corrosion basics [10]

The rate of corrosion is proportional to the amount of current flowing in the corrosion cell.

The rate of corrosion depends on the following:

- The metal (different metals corrode at different rates).
- The electrical resistance of the electrolyte.
- The amount of dissolved oxygen in the electrolyte.
- The pH (parts of hydrogen indicating acidity) value of the electrolyte.

The size of the corrosion cell can range from microscopic to long line cells over large distances.

2.2.3 Oxidation and reduction reaction

Oxidation refers to the loss of one or more electrons from an atom or molecules, a positively charged ion. When electrons are given up or released by an atom, that process is called an oxidation reaction. In a cathodic protection system, this reaction takes place on an anode.

The gaining of one or more electrons to an atom, which a negatively charged ion or neutral element, is known as place on a cathode [13].

2.2.4 Anodic process

When corrosion occurs, positively charged ions leave the anode (metal) and leave a surplus of negatively charged electrons through the metallic path to the cathode [13]. Figure 2.4 illustrates the anodic process. This anodic reaction for iron can be represented by:

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

Iron Ferrous Iron Electrons

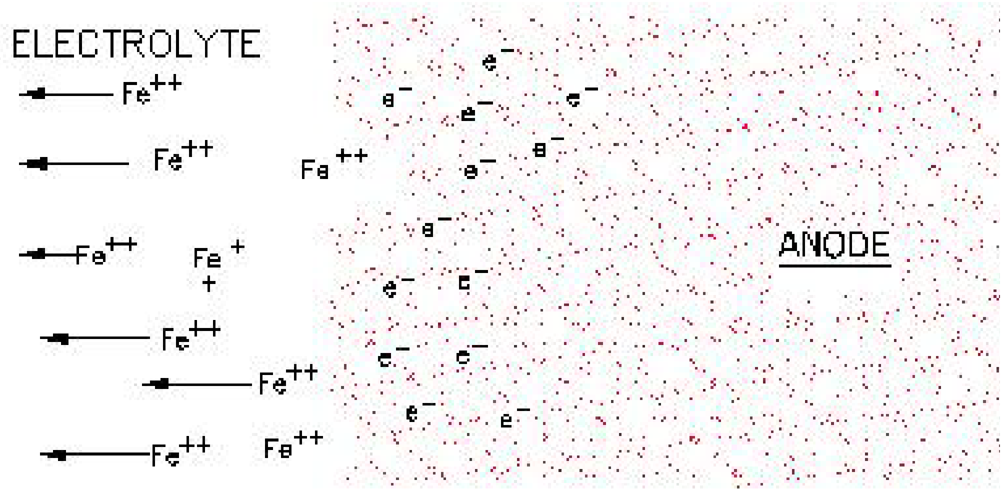


Figure 2.4: Anodic process [12]

2.2.5 Cathodic process

The electrons produced by the anodic reaction pass through the metal to the cathode surface where they restore the electrical balance of the circuit by reacting with and neutralising positive ions in the electrolyte [12]. Figure 2.5 illustrates the cathodic process. There are cathodic reactions, namely:

- Hydrogen ion reduction is the main cathodic process observed in acidic solutions, where the metal dissolves giving off hydrogen gas.

  $2H^{+} \quad + \quad 2e^{-} \quad \rightarrow \quad H_2 \uparrow$

  Hydrogen Ion Electrons Hydrogen Gas off

- The most important and commonly observed cathodic process in neutral or alkaline aqueous environments is the oxygen reduction process:

O_2 + $2 H_2O$ + $4e^-$ → $4 OH^-$

Dissolved oxygen Water Electron Hydroxyl Ions

- Corrosion is accompanied by the formation of solid products by the interaction of anodic and cathodic products.

$Fe^{++} + 2 OH^- \rightarrow Fe(OH)_2 \downarrow$

- Which is then further oxidised to form hydrated ferric oxide:

$4Fe(OH)_2 + 2H_2O \rightarrow 4Fe(OH)_3$

Ferric Hydroxide

- This compound is unstable and loses water to form ferric oxide or rust, (Fe_2O_3):

$2Fe(OH)_3 \rightarrow Fe_2O_3 + 3 H_2O$

Note that the electrons required for all the cathodic processes are supplied from the anodic Process, i.e. one cannot take place without the other. It follows, therefore, that if either the anodic or cathodic process is stopped or cannot take place, then the overall corrosion process will also be halted [12].

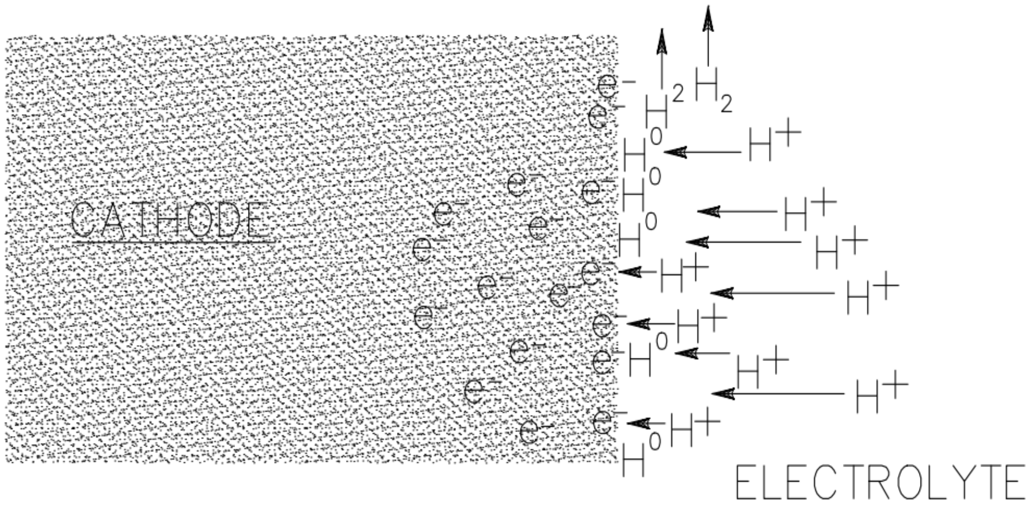


Figure 2.5: Cathodic process [12]

2.2.6 Combined anodic and cathodic process

At the cathode surface the electrons would meet hydrogen ions from the surface. One hydrogen ion would accept one electron and be converted to a hydrogen atom which could enter the metal and lead to hydrogen embrittlement.

In most cases, it could combine with another hydrogen atom and become molecular hydrogen gas which would either cling to the surface or be released as a bubble. As this process continues, oxidation of the anode occurs and at the cathode there will be the reduction of hydrogen ions.

The formation of adherent hydrogen gas at the cathode in neutral solutions acts to slow down the corrosion process at the cathode. This also slows down the corrosion rate at the anode which cannot proceed at a higher rate than electrons can be consumed at the cathodic surfaces. Slowing down of cathodic reaction is called cathodic polarisation and is the most important factor in limiting current requirements of cathode protection systems.

2.3 Electrochemical circuit

The ions produced in oxidation and reduction are current carrying charges. An electrolyte is an ionising solution capable of conducting electricity. Electrolytes with higher ionisation have greater conductivity. This means that conductivity is directly proportional to ionisation of the electrolytes. Figure 2.6 shows a basic electrochemical circuit [13].

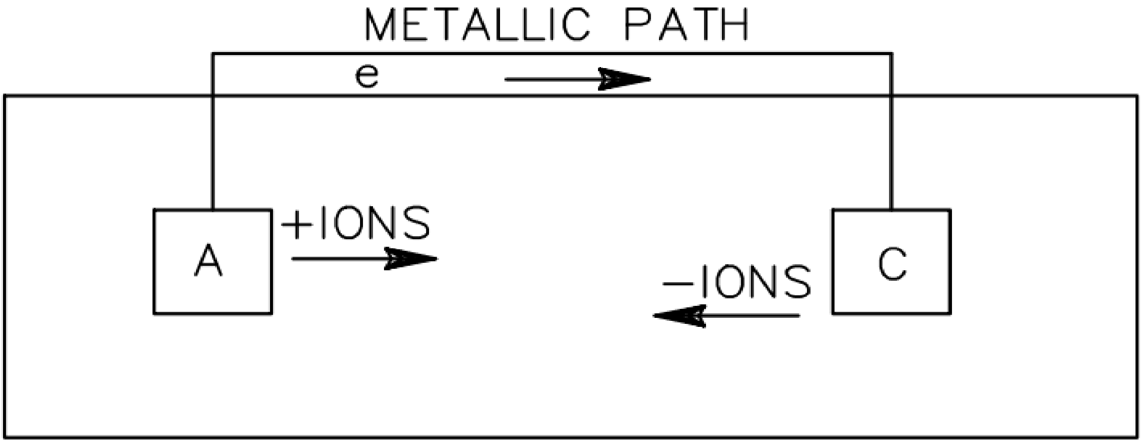


Figure 2.6: An electrochemical circuit [13]

Corrosion cell is a condition on a metal surface in which a flow of electric current occurs between the metal surface and an electrolyte with which it is contact to cause the metal to degrade. It consists of the anode, cathode, electrolyte and electronic or metallic path. An electrochemical process that includes the flow of electrons and ions is called corrosion. Metal loss takes place at the anode to protect the cathode. Anode is an electrode of an electrochemical cell at which oxidation occurs. Electrons flow away from the anode in the external circuit. Cathode is an electrode of an electrochemical cell at which reduction occurs and electrons flow toward the cathode in the external circuit.

The formation of metallic ions at the anode generates electrons that pass through the electronic path to the surface of the cathode locations immersed in water. They restore the electrical balance of the system by reacting with positive ions in the electrolyte. Figure 2.7 shows the corrosion cell [14].

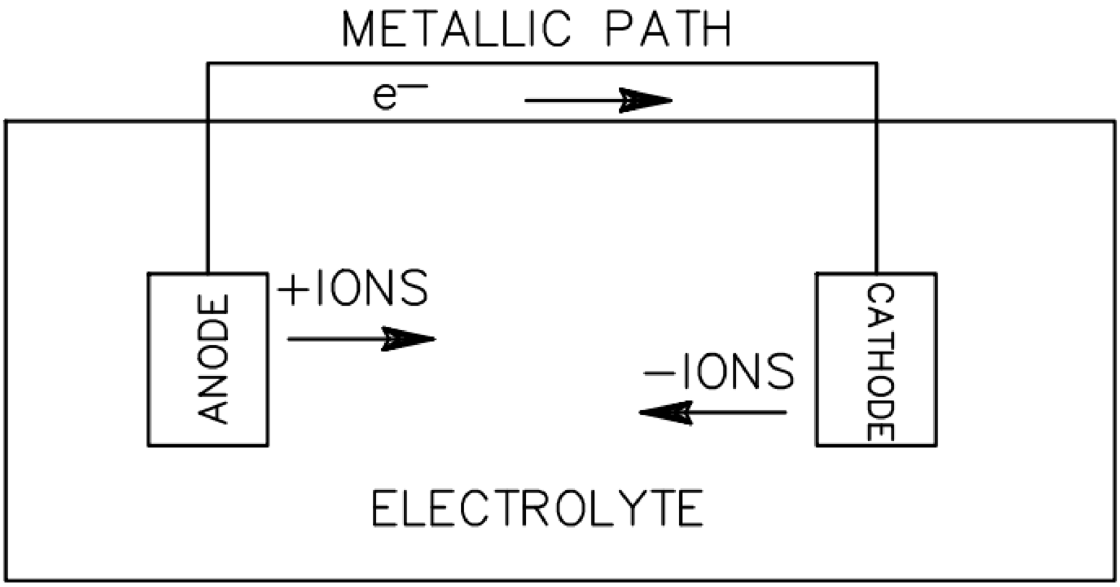


Figure 2.7: Corrosion cell [14]

2.4 Corrosion process using copper and iron rod

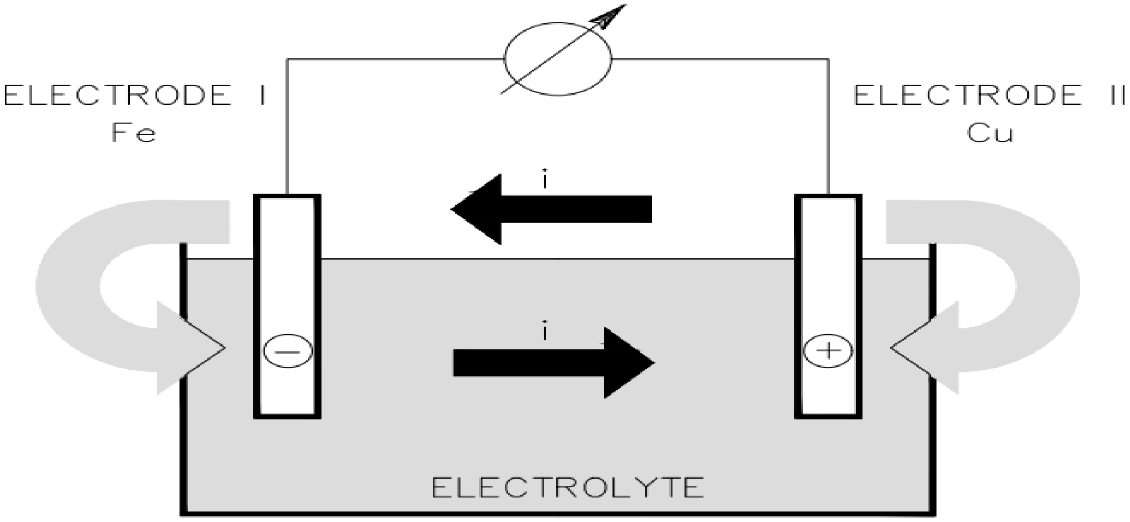


Figure 2.8: Corrosion process using galvanic cell [15]

Corrosion processes can be clearly explained with the help of a galvanic cell. If, for example, a metal rod is immersed into an electrolyte, positively charged ions pass into the electrolyte and conversely, positive ions are absorbed from the electrolyte by the metal band. In practice, potentials of the metals in the ground are measured with the help of a copper sulphate electrode which either consists of a copper rod, which is immersed in a copper sulphate solution, or of a copper sulphate dry electrode. The reference potential of this reference electrode remains constant.

If two rods made of different metals are immersed into the same electrolyte, a voltage develops in each rod. The voltage between the rods (electrodes) can be measured with the help of a voltmeter. It is the difference between the potentials of the individual electrodes compared to the electrolyte.

If, as can be seen in Figure 2.8 above, the copper electrode and the iron electrode are connected via an ampere meter outside the electrolyte, current flows within the external circuit from plus to minus poles, i.e. from the “more noble” copper electrode to the “less noble” iron electrode [15].

In the electrolyte, by contrast, the current must therefore flow from the “more negative” iron electrode to the copper electrode to close the circuit. [16].

2.5 Galvanic series

In this series, the metals are arranged from less active to the most active. Table 2.1 represents the standards emf series of the potential difference between metals exposed to solutions containing the respective ions at unit activity.

Table 2.1: Partial standard emf series of metals [17]

Metal	Standard Electrode Potential Eo (V) vs. SHE
Gold	+1.498
Platinum	+1.200
Copper	+0.345
Hydrogen	0.000
Lead	-0.126
Nickel	-0.250
Iron	-0.440

Zinc	-0.763
Aluminium	-1.662
Magnesium	-2.363

Electrochemical reactions will occur on each electrode, when two electrodes are placed in the electrolyte. When copper and zinc electrodes are immersed in the electrolyte, each will corrode and exhibit an electrode. The potential between the two electrodes is called electromotive force (emf). It is equal in sign and magnitude to the electrode potential of the anode less the electrode potential of the cathode. This emf between the two electrodes is the driving force for electrochemical corrosion [17].

2.6 Charge flow in an electrochemical corrosion cell

If an electronic or metal path connects the two electrodes, the voltage difference will cause a current to flow between them. Corrosion requires an electrical circuit, involves flow of current via free electrons. Any two metals will cause a current to flow due to relative tendencies to ionise.

Figure 2.9 shows a corrosion cell of iron and zinc in an electrolyte. The potential difference is -0.323V when zinc and iron are immersed in electrolyte using Table 2.1. The standard electrode potential. The potential difference between the electrodes will be $E_{cell} = E_{Zn} - E_{Fe} = (-0.763 - (-0.440) = -0.323V)$. When these two different metals are electrically interconnected in a common electrolyte, the more active metal (zinc) will tend to become the anode of the corrosion cell as illustrated in Figure 2.9. [18].

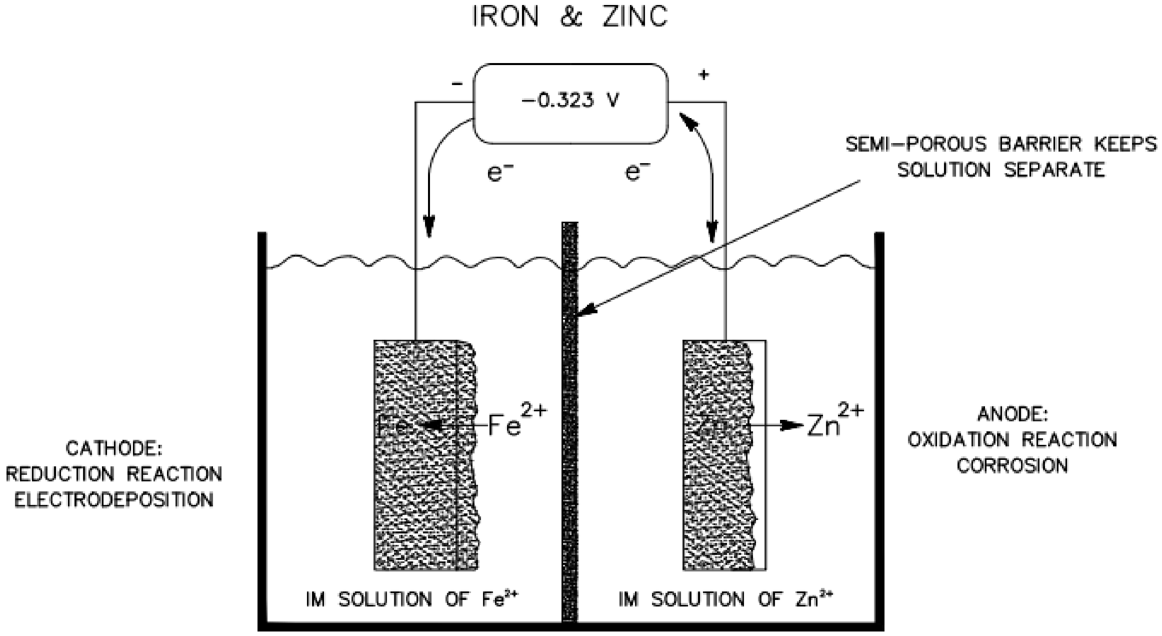


Figure 2.9: Oxidation and reduction reaction in a corrosion cell [18]

The partial standard emf series is a means of organising metals in order of their ability to corrode. A more effective method of arranging metals is the galvanic series. Copper-copper sulphate (Cu-$CuSO_4$) reference electrode and silver-silver chloride (Ag-AgCl) reference electrode are two of the standard half-cells or reference electrodes used for measuring the potential of a metal surface exposed to an electrolyte.

Copper sulphate is commonly utilised for measuring potentials of underground structures and those exposed to fresh water. It is not suitable to be used in chloride electrolyte as the chloride ions will migrate through the porous plug and contaminate the copper sulphate electrode. Silver-silver chloride is used for measurements in seawater.

Galvanic series is based on the particular behaviour of a metal in a particular electrolyte and the most common electrolyte used is seawater, as shown on Table 2.2.

Table 2.2: Practical galvanic series in sea water [19].

Metal	Volts vs. Cu-CuSO4 Reference Electrode	Volts vs. Ag-AgCl Reference Electrode

	Active or Anodic End	Active or Anode
Magnesium	-1.60 to -1.75	-1.55 to -1.70
Zinc	-1.10	-1.05
Aluminium	-1.05	-1.00
Clean carbon steel	-0.50 to -0.80	-045 to -0.75
Rusted carbon steel	-0.30 to -0.50	-0.25 to -0.45
Cast/ Ductile iron	-0.50	-0.45
Lead	-0.50	-0.45
Steel in concrete	-0.20	-0.15
Copper	-0.20	-0.15
High silicon iron	-0.20	-0.15
Carbon, Graphite	+0.30	+0.35

2.7 Corrosion rate

Most of the corrosion of underground metals is caused by an electrochemical reaction. Corrosion occurs through the loss of metal ions at anodic areas to the electrolyte. Cathodic areas are protected from corrosion because of the deposition of hydrogen or other ions that carry current. Soil resistivity, soil pH value, moisture, aeration, stray currents, presence of biological species, presence of sulphates and chlorides are the factors affecting underground corrosion [20, 21]. The following are the standard industrial protection criteria for buried steel structures:

- Potential of the structure ≥ 850 mV with respect to $Cu/CuSO_4$ reference electrode
- Positive potential shift of ≥ 100 mV when the current is interrupted [2].

The criterion for corrosion reduction is polarising the entire structure to the open circuit potential of the most active anodic site on the structure. Laboratory surveys have indicated the most active corrosion potential of a new steel in different soil environments is between -800 mV and -850 mV_{CSE} both referenced to a saturated copper sulphate reference electrode. At least a negative of -850 mV_{CSE} polarisation of a steel structure surface and stable copper sulphate reference electrode contacting electrolyte need to be obtained to ensure that the structure is adequately protected. Voltage drops (I_R drops) other than those across the structure-to-electrolyte boundary must be considered for analysis.

$$E_{-850} = E_{on} - IR$$

During laboratory experiments and a field survey for operating cathodic protection systems, it has been found that for old structures, the most active anodic site can be significantly more noble than -850 mV_{CSE}. A minimum of 100 mV of polarisation on an old structure should provide adequate cathodic protection if testing between the structure surface and stable reference electrode contacting the electrolyte to satisfy the second criteria.

$$\Delta E_{100} = E_{OFF} - E_{DEPOLARIZED}$$

or

$$\Delta E_{100} = E_{OFF} - E_{CORR}$$

2.8 Electrochemical equivalents

Table 2.3 shows theoretical estimated consumption rate per year for various metals when buried underground.

Table 2.3: Consumption rate for various metals [2]

Reduce species	Oxidized species	Molecular weight, M(g)	Electrons transferred (n)	Equivalent weight, M/n(g)	Theoretical consumption Rate (Kg/A-y)	Theoretical consumption Rate (Ib/A-y)
Al	Al^{+++}	26.98	3	8.99	2.94	6.48
Cd	Cd^{++}	112.4	2	56.2	18.4	40.56
Be	Be^{++}	9.01	2	4.51	1.47	3.24
Ca	Ca^{++}	40.08	2	20.04	6.55	14.44
Cr	Cr^{++}	52.00	3	17.3	5.65	12.46
Cu	Cu^{++}	63.54	2	31.77	10.38	22.88
Fe	Fe^{++}	55.85	2	27.93	9.13	20.13
Pb	Pb^{++}	207.19	2	103.6	33.85	74.63
Mg	Mg^{++}	24.31	2	12.16	3.97	8.75
Ni	Ni^{++}	58.71	2	29.36	9.59	21.14
Zn	Zn^{++}	65.37	2	32.69	10.7	23.59

2.9 Voltage difference

A voltage can be measured between different metals in an electrolyte. It can also be measured between a metal to a reference electrode both contacting the same electrolyte [23].

2.10 Copper-copper sulphate electrode

The purpose of the reference electrodes is to measure and monitor the pipeline condition through an auto-control/rectifier unit. It is the most commonly used reference electrode for measuring potentials of the underground structures and for those exposed to fresh water. A copper-copper sulphate electrode is generally used for measuring the pipe-to-soil potentials and the performance of the impressed current cathodic protection systems.

The number of reference electrodes has to be decided based on the exposed conditions, type of coating applied, etc. The number and position of reference electrodes and inert anodes on the underground pipelines is of utmost importance in designing an efficiently impressed current cathodic protection of any structure. Figure 2.10 illustrates how structure-to-electrolyte potentials are measured using a copper sulphate reference electrode. Figure 2.11 shows copper sulphate reference electrode components [24].

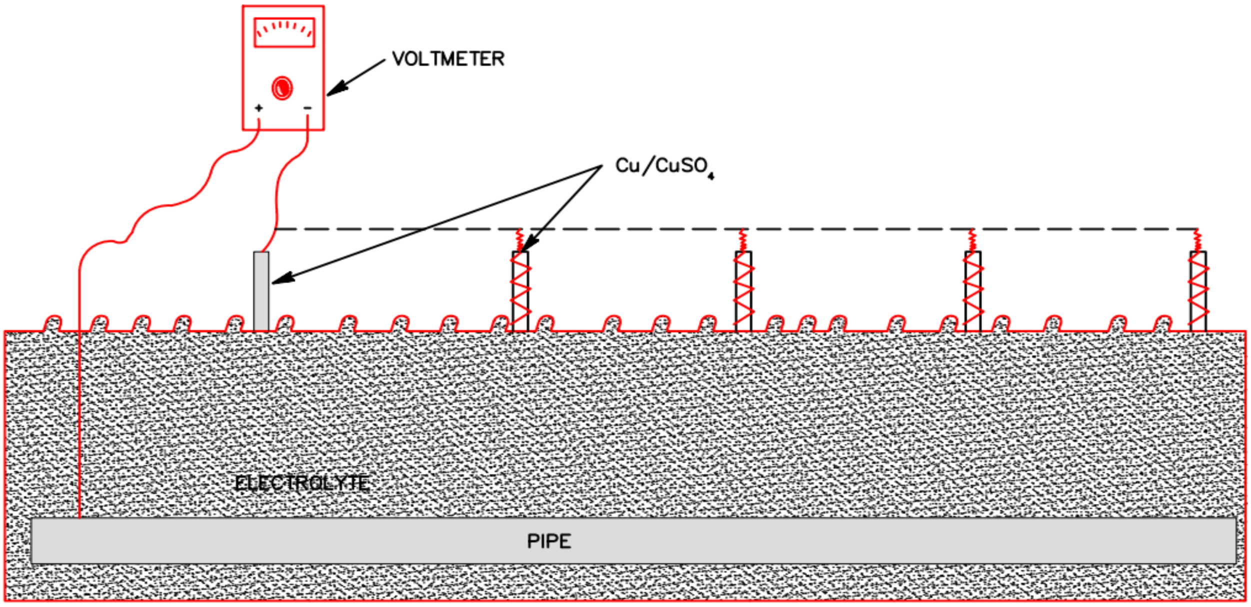


Figure 2.10: Potential measurements using a copper sulphate reference electrode [24]

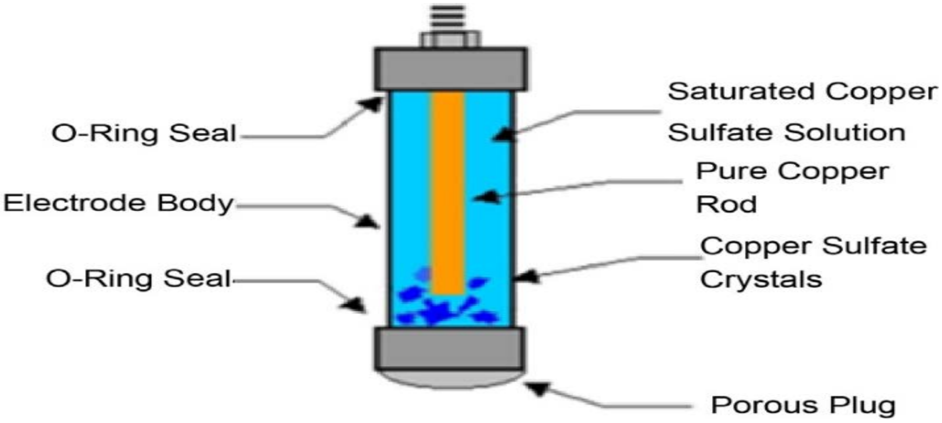


Figure 2.11: Copper sulphate reference electrode components [24]

A copper sulphate reference electrode is composed of a copper rod, immersed in a saturated solution of copper sulphate, held in a non-conducting cylinder with a non-reactive porous plug at the bottom. Copper ions in the saturated solution prevent corrosion of the copper rod and stabilise the reference electrode. Portable reference electrodes are utilised for field and laboratory testing purposes. They should be cleaned and refilled regularly.

Permanent reference electrodes are used for installation in or near a buried structure to monitor the structure-to-electrolyte potential. They need to be calibrated from time to time [24].

2.11 Converting between reference electrodes

Reference electrode conversion is done where more than one type of reference electrode is used. It is desirable to convert them all to the same reference, normally copper sulphate electrode. Half-cells or reference electrodes are the devices that permit measuring the potential of a metal surface exposed to an electrolyte. A structure-to-electrolyte potential is actually the potential difference between the structure and the reference electrode [25].

2.12 Polarisation

Polarisation is the change from the open circuit potential of an electrode resulting from the passage of current. As a current flow continues, polarisation occurs at both the anode and cathode. Polarisation lowers the potential difference between the anode and cathode areas, causing a reduction in the corrosion and the corrosion rate.

If the anode and cathode of a corrosion cell are connected, the resulting current will cause the potential of the anode to approach the potential of the cathode. As the resistances of the electronic or electrolyte paths reduce, the voltage difference between polarised electrodes also reduces, and both electrodes come to steady state polarised potentials.

The difference between polarised potentials of the anode and cathode is the driving voltage of the corrosion cell. The current at this steady state condition is defined as the corrosion current (I_{CORR}) of the system. The potential normally measured is a mixed potential (E_M) between the polarised anode potential (E_{PA}). Figure 2.12 is a graphical representation of the concept of polarisation [25, 26].

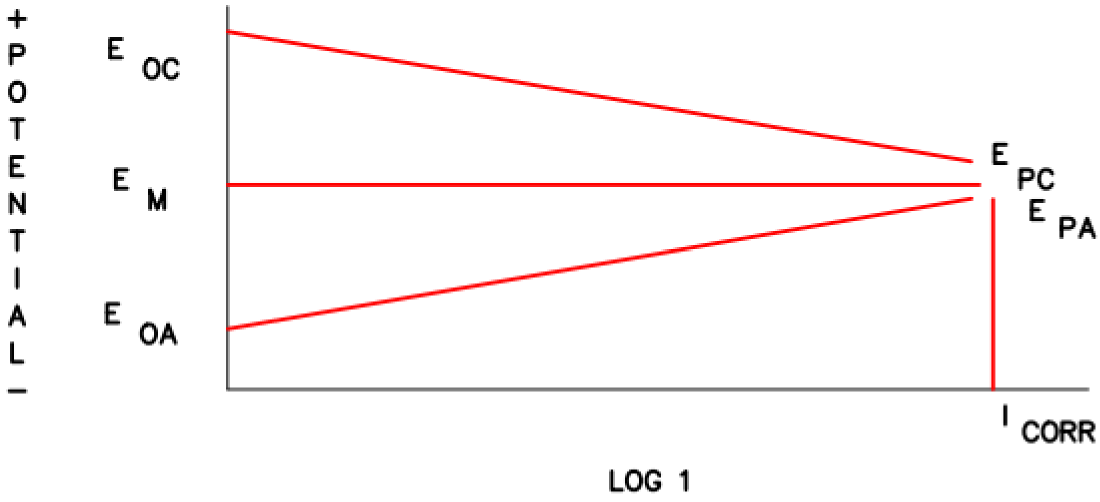


Figure 2.12: Concept of polarisation [25]

Open circuit potentials are the potentials of the cathode and anode, E_{OC} and E_{OA}, when the corrosion current is zero. E_{PA} is the polarised potential of the anode and E_{PC} is the polarised potential of the cathode.

I_{CORR} is the corrosion current of the corrosion cell. As the current increases, the value of E changes either anodically or cathodically depending on current direction. Polarisation is related to the depletion of the reactants and build-up of reactant products. Anything that favours the build-up of reaction products, or the depletion of reactants increases polarisation. Anything that causes the removal of reactants will reduce polarisation or depolarise.

The total polarisation of a structure is the sum of the activation and concentration polarisation. With the application of cathodic protection current, the reaction rate is relatively slow. In this case, the structure is most likely under activation control. However, as the cathodic protection current is increased, the availability of reactants at the interface decreases and reaction products start to accumulate, and concentration polarisation begins to control. As the current nears the limiting current density, the potential at the interface becomes more negative very fast [25, 27] [2].

2.13 Factors affecting polarisation

Factors that affect polarisation are: current or charge transfer, electrolyte resistivity (total ion concentration), anode or cathode ratio, temperature, effect, relative electrolyte, etc. Since polarisation is caused by current, as current increases, polarisation increases. A greater current result in a high reaction rate, causing a depletion of reactants and a build-up of reaction products.

Where the controlling factor is current, an increase in current causes an increase in polarisation. Where the controlling factor is polarisation, an increase in polarisation will cause a decrease in current. Since the transfer of charge or current through the electrolyte depends on ions, the total number of ions present will have a significant impact on the electrolyte resistivity and current flow in the circuit. An increase in ions will result in a decrease in resistivity.

Since polarisation is a function of the current density or current per unit area, the effect of current concentrated on a small area will be greater than the effect of the same amount of current on a larger area. A coated structure will polarise more rapidly than a bare structure with a given amount of current.

For corrosion cell, the area ratio of anode and cathode is important. A small anode and large cathode is undesirable because the pitting is greater compared to a large anode and small cathode [13, 27]

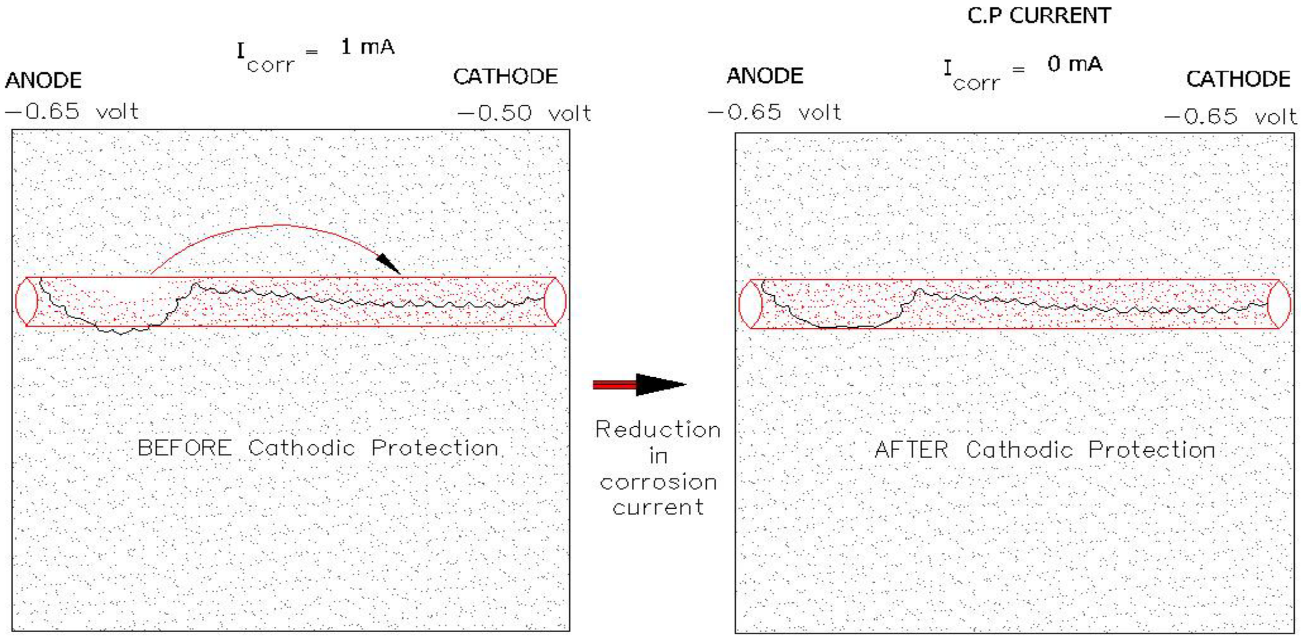
2.14 Cathodic protection concept

Cathodic protection involves reduction of potential difference between the anodic and cathodic locations to zero, resulting in a zero-corrosion current flow. This is achieved by impressing current onto the structure from external electrode and polarising the cathodic locations or sites in an electronegative direction.

As the potentials of the cathodic location or area polarise towards the potentials of the anodic area, the corrosion current is reduced. In simple words, the current is impressed into the structure to reduce the potential difference between anodic and cathodic sites.

When the potentials of all cathodic locations reach the open circuit potential of the most active anodic areas, corrosion is eliminated on the structure. Corrosion of the structure will be minimised once the applied cathodic protection current equals or exceeds the corrosion current.

Cathodic protection current is impressed from an external cathodic protection anode through the electrolyte to the metal and reduces the potential difference between anodic and cathodic sites, as shown in Figure 2.13, diagram a and b. Diagram a of Figure 2.13 shows the status of the structure to be protected before cathodic protection has been applied. Diagram b of Figure 2.13 shows the status of the structure after cathodic protection has been applied [2, 27].



2.13a **2.13b**

Figure 2.13: Cathodic protection applied to a structure (a) before CP and (b) after CP [2]

2.15 Objectives of cathodic protection

The following objectives must be achieved in a cathodic protection system that is adequately designed to prevent corrosion:

- To prevent external corrosion through the design life of the pipeline.
- To provide sufficient current to the protected pipeline and distribute this current so that the selected criteria for the CP system are effectively attained.
- To provide sufficient current to the structure to be protected.
- To minimise the interference currents on nearby underground structures and from other sources of DC current.
- To have an anode system with life similar to the required life of the protected structure, or provide for periodic rehabilitation of the anode system
- Allow for changes in current requirements with time.
- Ensure anodes are not distributed or damaged. and other structures have not been installed close to them.
- Ensure that the CP system operates continuously.
- To prevent external corrosion through the design life of the pipeline

The above are achieved by shifting the potential of the metal in the negative direction with respect to earth by the use of an external DC power source to impress a current on the structure [25, 28, 29].

2.16 Polarisation of a structure

Current must flow from the DC power source to the structure, via the anodes, to be protected. When current goes from the electrolyte to the metal, a reduction reaction occurs. Products from these reactions change the chemical composition of the electrolyte at the structure/electrolyte surface. The chemistry at the interface, as measured by the structure potential, is known as polarisation. Figure 2.14 illustrates the polarisation process of an underground structure [2, 27, 30].

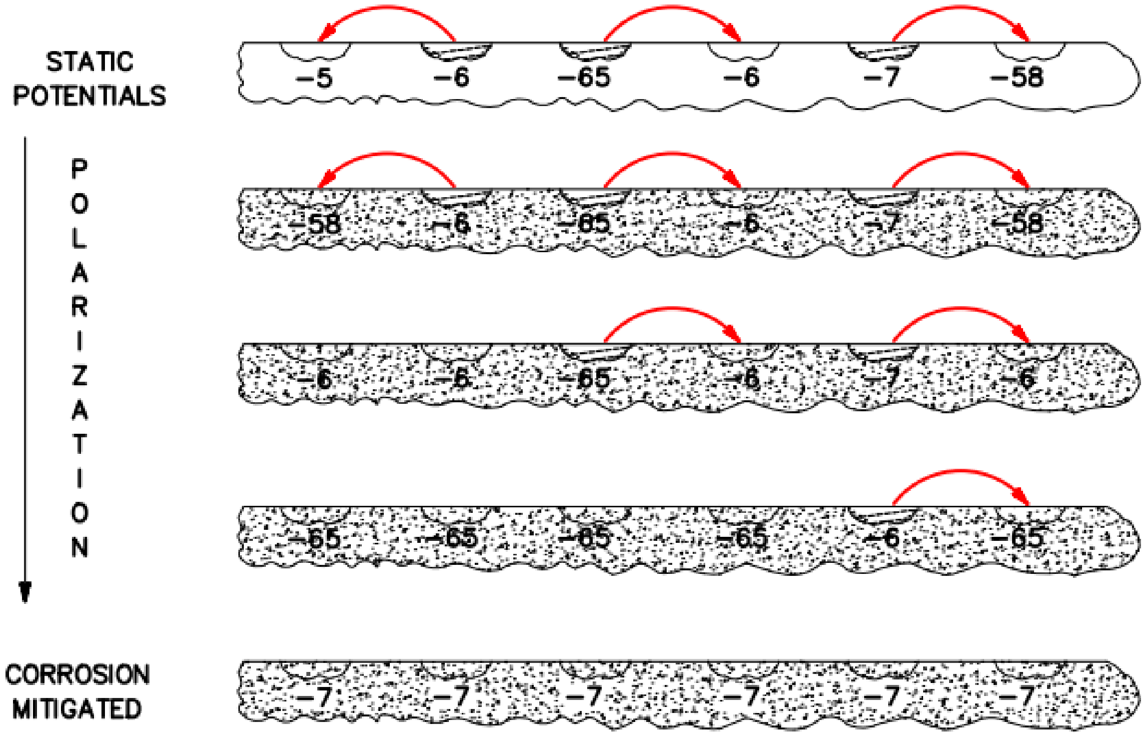


Figure 2.14: Polarisation of underground structure [27]

As the structure polarises, its potential changes in an electronegative direction as illustrated on Figure 2.14. For mitigation of corrosion, all existing cathodic areas must be electro negatively polarised to a potential equal to the open circuit potential of the most active anode potential existing on the structure [2, 31].

Polarisation of the structure is implemented by applying external current, the magnitude of which depends on the cathodic polarisation behaviour. Polarisation of the cathodes to the open circuit potential of the anodes is the true criterion for eliminating corrosion.

Because corrosion cells are usually microscopic and the measured potentials are corrosion potentials (Ecorr), the initial measurements are most likely to be average of corrosion potentials for several corrosion cells. The several replacement or surrogate criteria were developed to assist meeting the true criteria [26, 27]. Figure 2.15 shows the structure of polarisation formation.

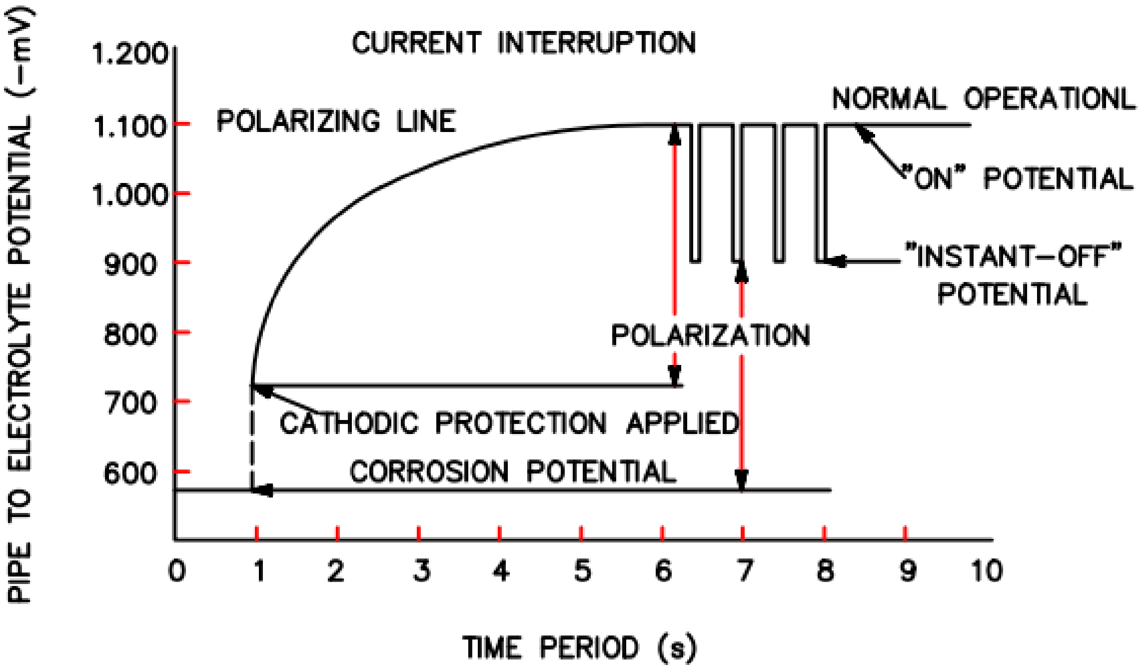


Figure 2.15: Polarisation formation [2]

2.17 Adequate protection current requirement

The amount of current required to provide an adequate protection depends on the surface area to be protected and the polarisation behaviour of the structure in its environment. Current requirement is directly proportional to the area of the exposed metal surface to the electrolyte. A good-coated structure requires less current than a bare structure and a coated structure needs a protective current only at coating holidays, meaning defects in the coating defects [26].

2.18 Applied current versus corrosion rate

The first increment of applied cathodic protection current results in the largest decrease in corrosion. Cathodic polarisation at potentials more electronegative than the static anode potential has no benefits and, in extreme cases can be harmful to the structure and/or its coating. This is known as overprotection and it can be harmful to atmospheric metals and alloys which may corrode at high rates in both basic and acidic environments.

Overprotection can cause coating disbondment and this depends on the particular coating. Structure coatings polarised potential values more negative than -1.200 mV $_{\mathrm{CSE}}$ should be avoided [26].

Based on underground structure coatings, the coating manufacturer should be consulted to determine if the coating is compatible with cathodic protection. Excessive protection can lead to hydrogen damage of some metals. If all of the cathodic locations have polarised to the open circuit potential of the most active anodic locations, corrosion is mitigated but it is not possible to measure the potential of the individual anodes and cathodes. A surrogate criterion is therefore required. Figure 2.16 illustrates the logarithmic relationship between cathodic protection current and corrosion rate [2, 32].

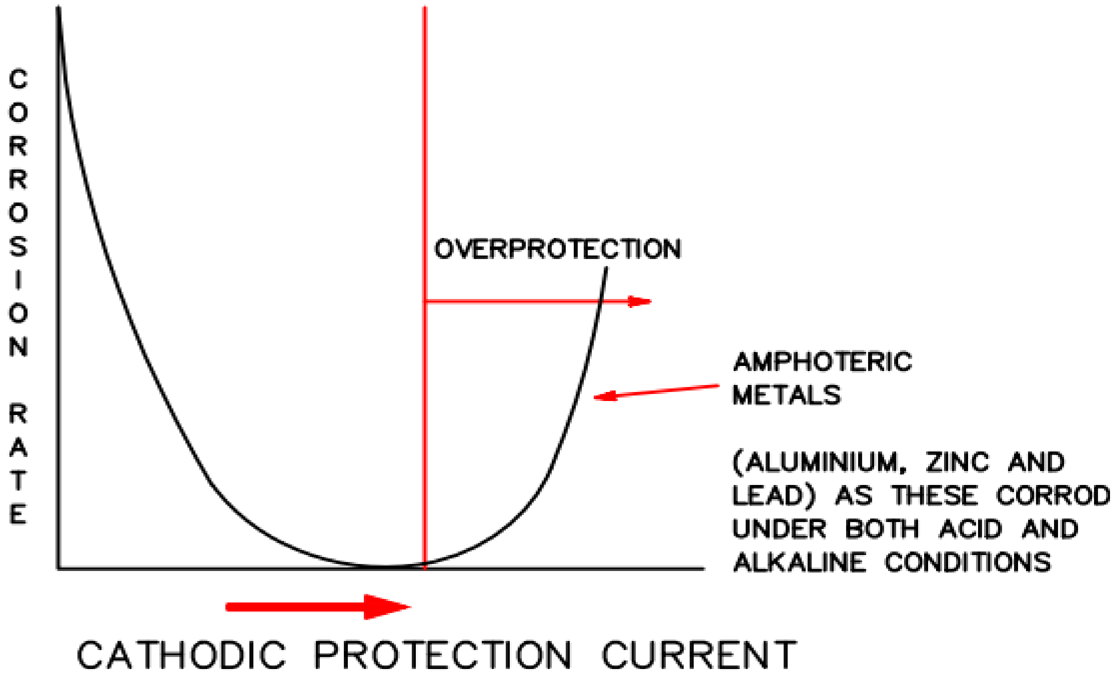


Figure 2.16: Cathodic protection current versus corrosion rate [2]

2.19 Primary criteria for cathodic protection

Based on the NACE standard SP0169 and TM010, cathodic protection criteria that apply to steel involve structure-to-electrolyte potential of equal to or more negative than

-850 mV in reference to a copper sulphate reference electrode (CSE) and one is a polarisation change of 100 mV. There are three primary criteria for cathodic protection of underground or submerged steel or cast-iron piping, namely:

- -850 mV $_{CSE}$ with CP applied
- A polarised potential of -850 mV $_{CSE}$
- 100 mV of polarisation.

The criterion which is used to determine the efficiency of a cathodic protection system is known as the structure to electrolyte potential. The potential difference is measured using a high impedance voltmeter and a reference electrode, normally saturated copper/copper sulphate ($Cu/CuSO_4$).

The primary protection criterion of a polarised potential of at least -850 mV and not more than -1200 mV shall be achieved on all parts of the buried pipeline (refer to Clause 6.2.2.1.2 of NACE RP0169). All potential values are measured relative to a $Cu/CuSO_4$ reference electrode (CSE).

Based on the NACE RP0169 requirements of Clause 6.2.2.1.3, a minimum of 100 mV of cathodic polarisation exists between the structure surface and stable reference electrode contacting the electrolyte. The formation or decay of polarisation can be measured to satisfy this criterion This criterion may be applied to determine whether cathodic protection has been successfully achieved.

This other criterion should be utilised only when it is not possible to achieve a polarised potential of -850 mV (CSE). With specific regard to pipeline sections in high-resistivity aerated sandy soil conditions, less negative values may be acceptable [2, 25].

2.19.1 -850 mV $_{CSE}$ with cathodic protection applied

A negative (cathodic) potential of at least 850 mV with the CP applied is required for this criteria. This potential is measured with respect to a saturated copper sulphate reference electrode contacting the electrolyte.

The voltage drop (IR drop) between the reference electrode and structure-to-electrolyte boundary are an error in this reading and must be removed before applying this criterion.

However, in the presence of sulphides, bacteria, elevated temperatures, acid environment and dissimilar metals, the criteria of –850 mV may not be sufficient [2, 25].

2.19.2 Polarised potential of -850 mV criteria

Beavers, Holtsbaum and NACE-RP-0169 agree that a negative polarized potential of at least -850 mV relative to a saturated copper sulphate reference electrode contacting the electrolyte to determine whether cathodic protection has been successfully achieved [25].

This can be obtained by interrupting all current sources influencing the structure and taking an instant off potential. This criterion is more direct than the -850 mV criteria with CP applied by clearly defining the method by which voltage drops errors in the ON potential are considered.

The disadvantage of this criterion is the requirement that all sources of DC current be interrupted. A potential more negative than -850 mV_{CSE} may be required to mitigate corrosion in the presence of MIC, further increasing the likelihood of overprotected [25, 31, 33].

2.19.3 100 mV of polarisation criteria

A minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte [31]. It has been found from the laboratory and test results from operating cathodic protection systems, that a minimum of 100 mV of polarisation on the old structures should provide adequate cathodic protection. This is because for older structures, the most active anodic site can be significantly more noble than -850 $mV_{CSE.}$

It is also applicable for metals other than steel and with reference cells other than copper sulphate. Polarisation is the change in potential from the native or free corroding potential and the instant OFF potential. This criterion has the sound fundamental basic.

The corrosion rate decreases and the rate of the reduction reaction on the metal surface increases as the underground structure is polarised in the negative direction from the native potential. It can be measured during formation or decay, as shown on Figure 2.17, which is a graphical representation of cathodic protection criteria of 100 mV and -850 mV criteria curve [25, 27, 34, 35].

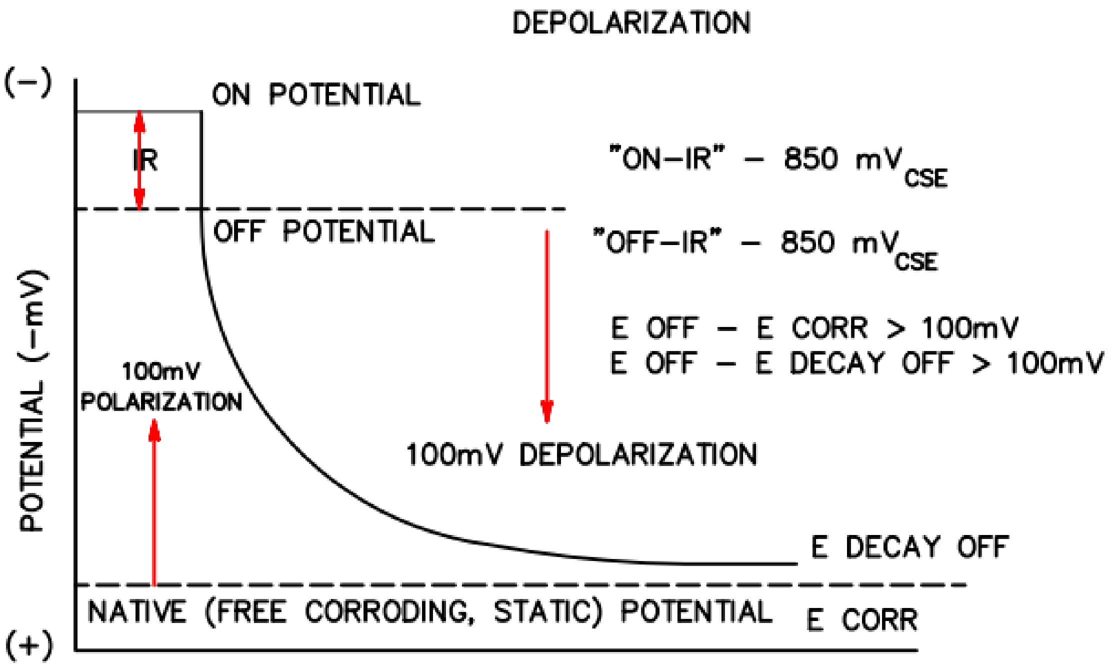


Figure 2.17: Cathodic protection criteria curve [27]

2.20 Potential limits for cathodic protection of pipelines

For steel pipelines to be considered fully cathodically protected, the "OFF" potential on all parts of the pipeline should be within the ranges indicated in the 'protection achieved' row, as stated in Table 2.4 [27].

Table 2.4: Potential limits for cathodic protection of pipelines [27]

Range of protection	Silver-silver chloride reference (mV)	Copper–copper sulphate reference electrode (mV)
Corrosion (under protection)	> -800	> -850
Protection achieved	> -800 < -1100	> -850 < -1200
Overprotection	< -1100	< -1200

2.21 Current density requirements

The complete protection of buried steel or iron may require 0.75-5.0mA of the current per square foot of the surface. On a well-coated line, the current may be as low as

0.01-0.2 mA/ft² [36]. Table 2.5 illustrates the current required for protection of steels in various environments.

Table 2.5: Current densities for steels protection in various environments [36]

Environment	Current density (mA/m²)	Current density (mA/ft²)
Soil	(40-58)	(0.75 - 5.0)
Freshwater	(11-32)	(1-3)
Seawater	(43-64)	(4-5)
Moving water	(11-32)	(1-3)
Sea mud	(11-32)	(1-3)

2.22 Cathodic protection systems

Galvanic or sacrificial and impressed current cathodic protection systems are the two primary types of cathodic protection systems [7, 29].

2.22.1 Galvanic cathodic protection system

2.22.1.1 Components of galvanic cathodic protection system

The anode, anode backfill, a means of connecting the anode to the structure and structure are the basic components of a galvanic anode cathodic protection system. Figure 2.18 is a typical galvanic anode cathodic protection system [25].

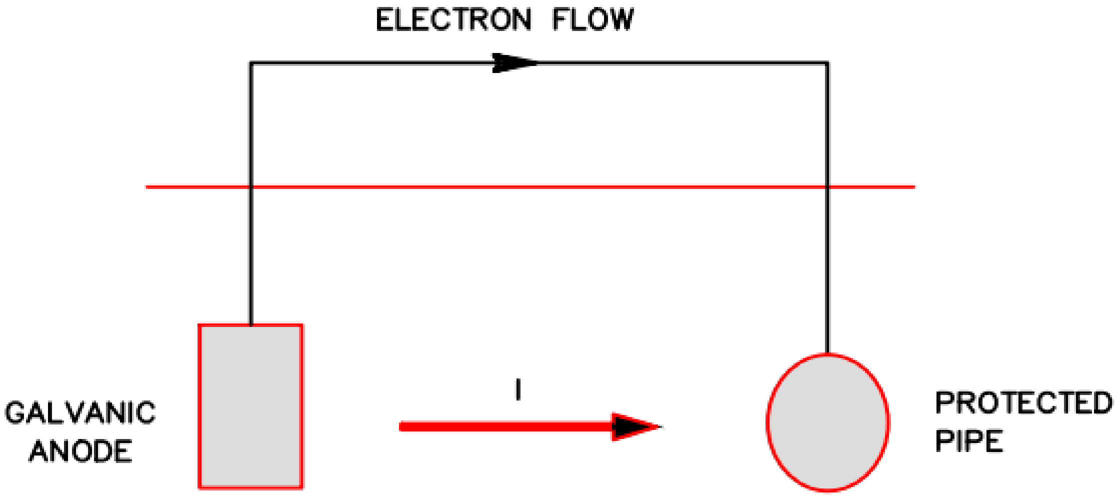


Figure 2.18: Typical galvanic cathodic protection system [25]

2.22.1.2 Principle of galvanic cathodic protection system

Sacrificial anode technique use the natural potential difference, derived from electrolysis that exists between the structure and a second metal in the same environment to provide a natural current that flows from the buried anodes to the structure. No external power source is employed.

In other words, a more active metal connected to a less active material will form a galvanic corrosion cell. This is utilised to protect the less active metal, or the noble metal gets protected with consuming the less noble metal. Aluminium, zinc, and magnesium alloys are more base materials than mild steel/carbon steel, which are the structural material for many pipelines, offshore structures, ships, etc. Figure 2.19 illustrates the principle of the galvanic cathodic protection system [7].

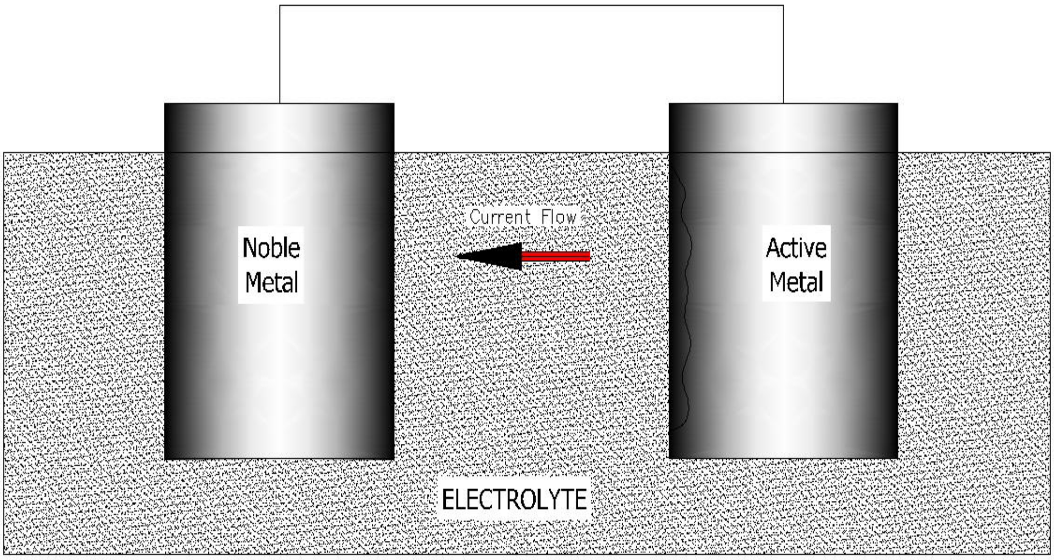


Figure 2.19: Principles of galvanic CP system [7]

The efficiency of a galvanic anode depends on the alloy of the anode and the environment in which it is installed. The consumption of any metal is directly proportional to the amount of current discharged from its surface. The efficiency of the magnesium anode is normally less than 50%, while zinc has an efficiency of 90%. Magnesium has a nominal corrosion potential of -1.75V referenced to a copper sulphate electrode and its application in soils and sea water. The galvanic anodes can be connected to the structure by directly welded or bolting integral straps [25].

2.22.2 Impressed current cathodic protection system

The impressed current cathodic protection (ICCP) system is the most reliable, flexible cathodic protection system for protecting underground pipelines from external corrosion. Its components are anodes (ground bed), anode backfill, a rectifier, reference electrode, structure to be protected, wiring and connections. Protective current drawn from the rectifier is impressed to the structure, which is connected to the negative terminal of the rectifier via the anodes connected to the positive terminal of the rectifier through the electrolyte. This develops an electrolytic cell.

The ICCP system anodes are made with materials that are consumed at low rates. ICCP systems operate higher current and driving voltage than galvanic CP systems. Figure 2.20 is a typical impressed current CP system [7, 27].

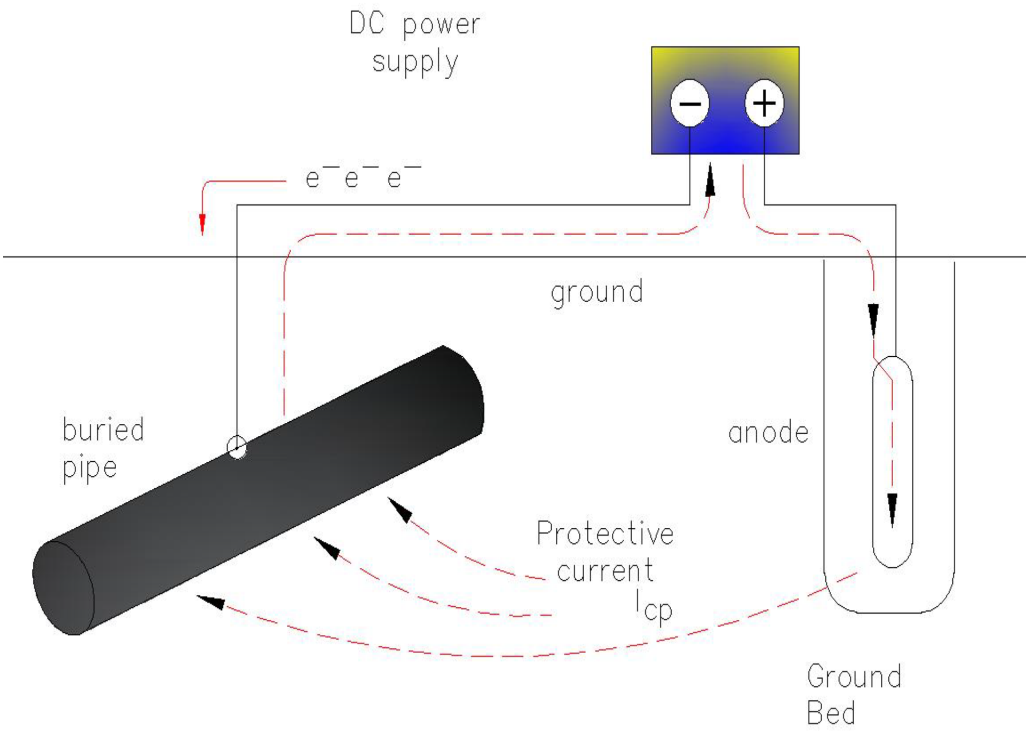


Figure 2.20: Schematic illustration of impressed current CP system technique [27]

ICCP is utilised for applications with large current requirements such as bare or poorly coated structures, in all electrolytes and resistivities to overcome stray current or cathodic interface problems, underground storage tanks, and offshore structures. Materials used for anodes in an ICCP systems include graphite, conductive polymer, high-silicon cast iron, mixed-metal oxide, platinum, and scrap metal.

The ICCP system has two types of anode ground bed configurations, which are distributed and deep anode ground bed. Areas where impressed CP system is used most effectively is in long distance pipelines, off shore structures, etc. [2, 37].

2.22.2.1 Distributed impressed current anodes

When designing distributed anode systems for an ICCP, effective soil resistivity along the section of pipeline to be protected should be known. Existing potentials to earth must be known along the section to be protected, so the earth potential changes needed to attain a minimum potential of -0.85V (pipe-to-close CSE) can be determined at the midpoint between anodes. The parallel resistance of all anodes is calculated.

With allowances for header cable resistance and back voltage between pipeline and anodes, voltage and current requirements of the power source may be calculated.

An important consideration in determining spacing between distributed anodes is the effect of earth potential change at midpoint between adjacent anodes [2, 27]. Figure 2.21 is a typical distribution ICCP system.

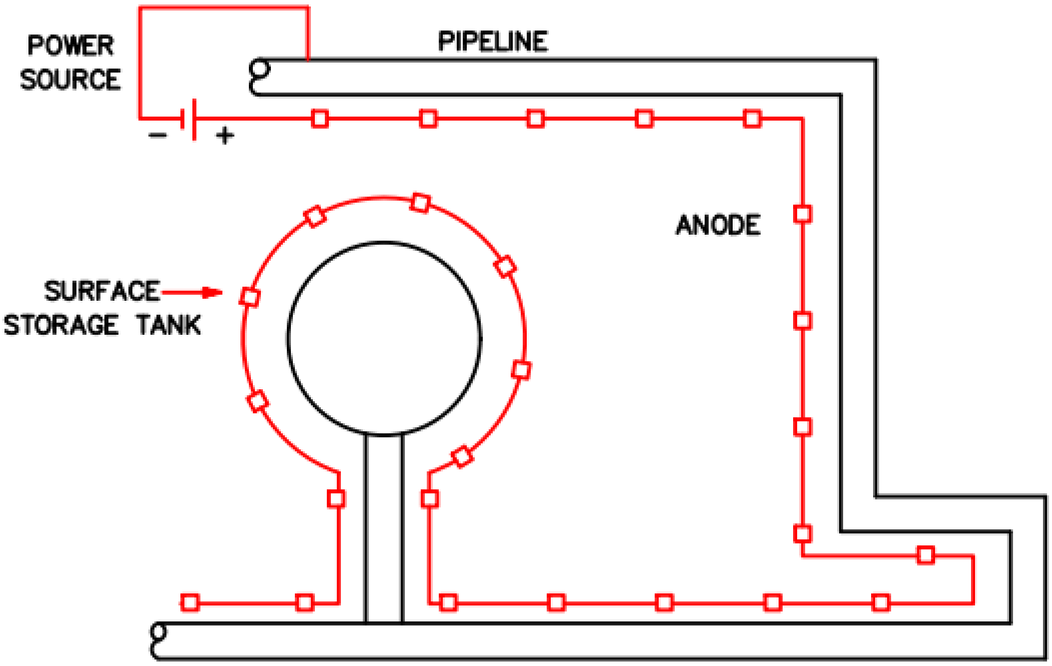


Figure 2.21: Typical distribution ICCP system [27]

Material used for ground bed construction can be carbon steel or noble materials plated with inert materials such as platinum or mixed metal oxides. For economic reasons and required service life, the material should have a low consumption rate at an acceptable cost. A list of the various materials and approximate current densities and consumption rates are provided in Table 2.6 [2].

Table 2.6: Typical consumption of impressed current anode material [2]

Impressed current anode material	**Maximum current density, A/m²**	**Working current density, A/m²**	**Consumption rate**
Steel	-	0.5	10kg/A.yr
Aluminium	10	4.8	2kg/A.yr
Graphite	25	2.5 to 10	0.25kg/A.yr
Silicon iron	50	5 to 25	0.1kg/A.yr
Magnetite	200	115	0.02kg/A.yr
Lead alloy	300	50 to 150	0.085kg/A.yr
Platinised titanium	2000	250 to 700	8mg/A.yr
Platinised tantalum or Platinised niobium	2000	500 to 1000	8mg/A.yr
MMO on titanium	1000	500 to 100	1mg/A.yr

2.22.2.2 Deep impressed current anodes

Deep anodes ground beds installed on small plots of ground or in an alley or parkway provide effective protection for coating, isolated pipe in a subdivision or other distribution area. This configuration can replace galvanic anodes that have reached end of life successfully in several areas without creating interference problems. These installations have been made quite successfully for gas piping in city streets and alleyways, as well as to upgrade underground tanks and piping in service stations.

Deepwell anode ground beds are specially designed and installed as part of an impressed current cathodic protection system to provide a relatively high amount of CP current to structure such as well casing. The selection of appropriate anode material is important to achieve long anode life based on consumption rates [27].

Figure 2.22 illustrates a typical example of deep anode ground bed in normal soil strata. Deep anode configuration utilises multiple anodes attached to a single header cable back to the rectifier from each end and this will increase design reliability [27].

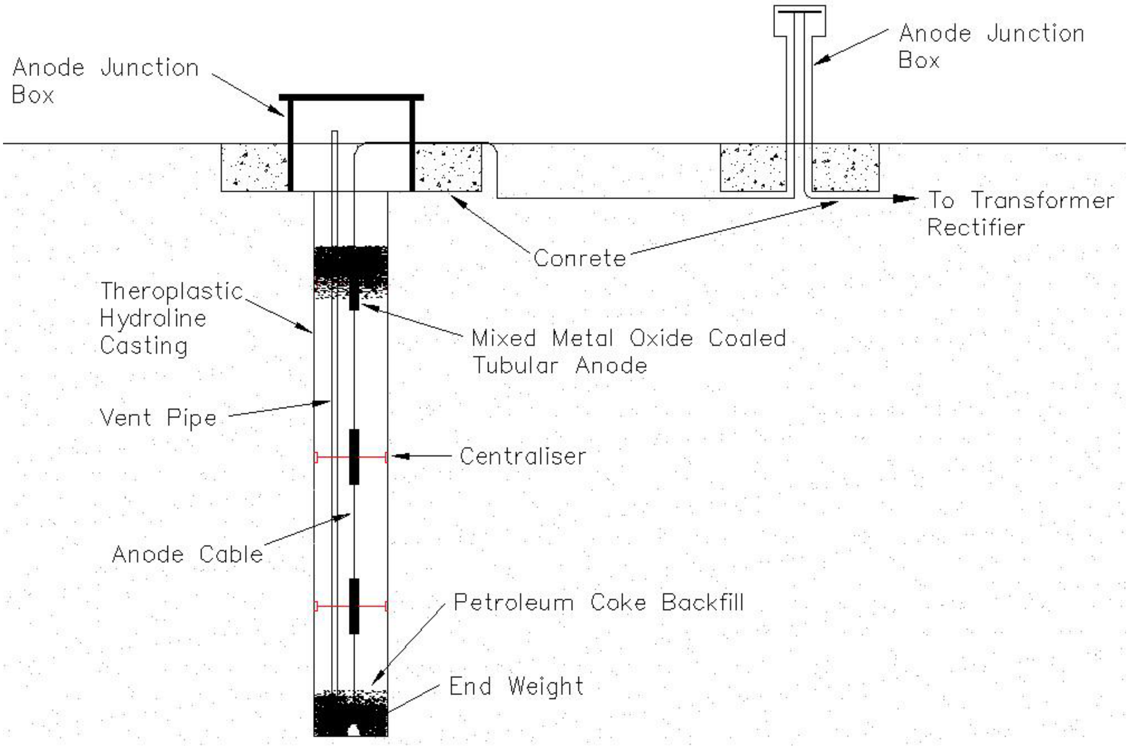


Figure 2.22: Typical deep anode ground bed in normal soil [27]

2.22.2.3 Uses and benefits of deep anodes

Deep anodes provide effective CP to facilities as diverse as underground pipelines, storage tanks refineries, power plants, treatment plants, pile structures and well casings in areas where surface soil resistivities are either very high or, if reasonably low, are shallow and overlie high resistivity material. These conditions require large surface anodes too far from the structure to obtain reasonably low resistance electrically remote from structure.

Installing multiple anodes in one carbon column achieves maximum anode current discharge balance. The high level of carbon compaction in deep anodes provides maximum electronic current discharge, thereby increasing anode life. The high probability for ground water provides the lowest possible circuit resistance. Properly installed venting systems minimise the risk of gas blockage and allow for anode irrigation with potable water. Inherently low circuit resistance of these anode systems minimises the costs of AC power consumption [30].

2.23 Impressed current anode design

Impressed current anode systems need to be designed so that their mass and quality are sufficient to last for the design life of the system. The resistance to earth needs to allow the maximum predicted current demand to be met without exceeding the voltage capacity of the DC source during the design life of the system and the location is at such a distance from the structure as to provide a regular distribution of current. Finally, the risk of causing harmful interference on other buried structures will be minimised [2, 30].

2.24 Anode backfill

The drilling and completion of the borehole and the installation of the anodes and backfill are specialised jobs that require an experienced team. The borehole design and construction need to be such that undesirable transfer between water bearing formations and pollution of underlying strata from the surface (e.g. tank farms) is prevented.

Metal or plastic casings are normally used at the surface for stabilising the borehole. Steel casing or perforated plastic casing is used in the active section of the ground bed. The casing at depth needs to be electrically isolated from metal surface casing and structures at the surface to avoid interference. For this isolation, plastic casing is normally used. Deep ground beds need to have venting pipe to prevent gas blocking of the well. These are normally made of chlorine-resistant plastic.

The backfill material of choice for impressed current anodes for underground CP applications is carbon. Its purpose is to reduce the resistivity of the environment surrounding the anode to increase the amount of current the anode can discharge, extend the anode surface area, thus increasing the amount of current the anode can discharge and reduce consumption of the anode since the carbon becomes the part of the anode consumed before the anode itself.

The higher the degree of compaction, the lower the resistance. Coke breeze is usually utilised for deep anode systems and particles may range from 0.10 to 1.0 mm in size. It is added during the installation of the anode bed by pumping a fluidized mixture of water and carbon backfill to the bottom of the hole and allowing the carbon particles to settle out.

Deep anode CP systems present environmental concerns as the borehole can penetrate different geological layers and water aquifers. The layer needs to be sealed to prevent the transfer of unwanted components. This needs to be done through utilisation of clay sealing material. The reactions at the anode surface are oxidation, oxygen and chlorine evolution and chlorine generation. These are flammable, poisonous or corrosive and can cause blockage on the ground bed, reducing anode performance [2].

These gases need to be removed or vented, especially in deep anode systems. Anodes need to be located to distribute current as evenly as possible to the structure to ensure current is distributed efficiently for cathodic protection. A distributed configuration utilises anodes located at relatively close intervals along the structure. The anodes are spaced close together and close to the structure so as to distribute the current evenly over the surface of the earth adjacent to the structure, as shown on Figure 2.23 [27].

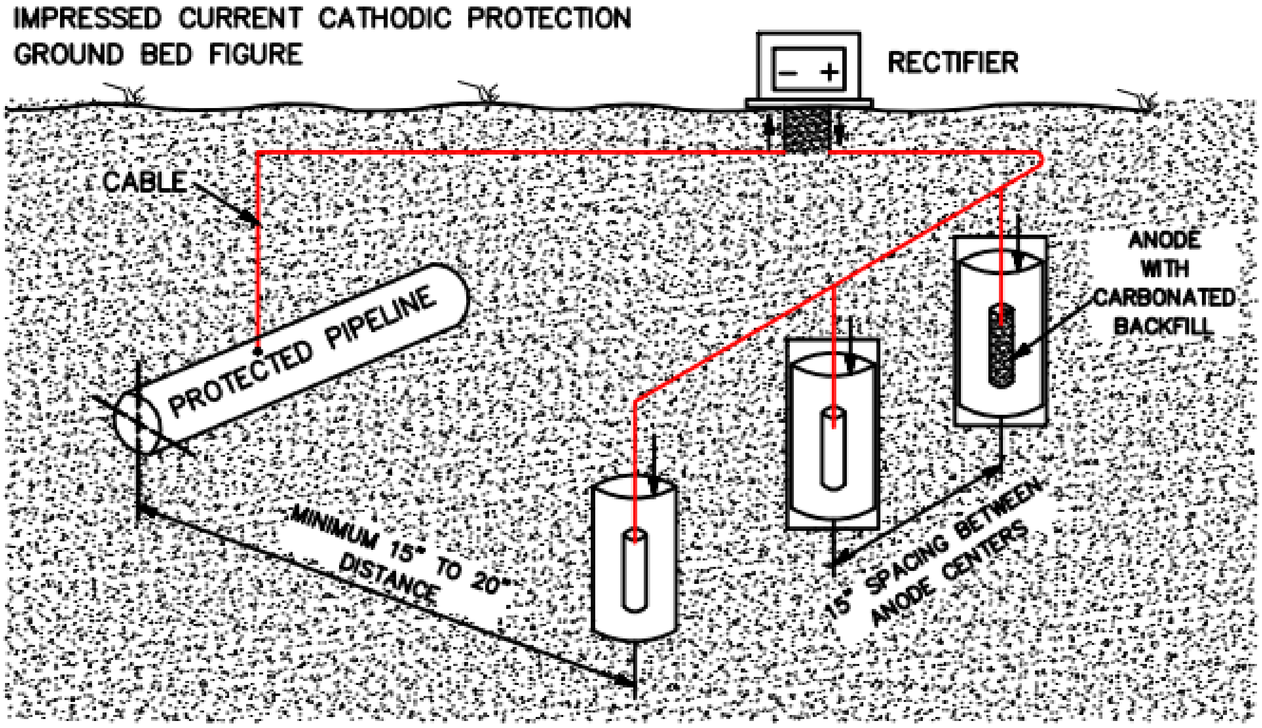


Figure 2.23: Typical illustration of a distribution anode system [27]

All anodes can be inserted either horizontally or vertically. This depends on the conditions present at the ground bed locations. Vertical ground beds require less room and less excavation, requiring auguring a hole rather than digging a ditch, and having a lower resistance than horizontal anodes installed under the same conditions. Impressed current anodes are used in remote configuration by installing them in a deep hole drilled from the surface and are known as deep anodes. They are at least 15.24m deep, while semi-deep ones are 7.62 to 15.24m in depth [27].

Current density requirements for cathodic protection of uncoated steel in various environments are listed in Table 2.7.

Table 2.7: Typical current requirements of uncoated steel in various environments[2]

Environment	**Current density, (mA/ft^2)**	
	AFM 88-9	**Gerrard**
Neutral soil	0.4 to 1.5	0.4 to 1.5
Well-aerated neutral soil	2 to 3	2 to 3
Wet soil	1 to 6	2.5 to 6
Highly acidic soil	3 to 15	5 to 15
Soil supporting active sulphate reducing bacteria	6 to 42	up to 42
Heated soil	3 to 25	5 to 25
Stationary fresh water	1 to 6	5
Moving fresh water	9 to 25	5 to 6
Turbulent fresh water containing dissolved oxygen	5 to 15	5 to15
Sea water	3 to 10	5 to 25

2.25 Transformer rectifier unit

A transformer rectifier is utilised as the power supply of an impressed CP system. A rectifier converts AC power supply voltage to the required output voltage and then converts it to DC. This is the key component in adjusting the performance of the impressed current cathodic protection system.

It also plays an important role during cathodic protection surveys to measure the level of protection on the protected structure and during commissioning of the new installed impressed current cathodic protection system. Figure 2.24 shows a single-phase bridge rectifier circuit. The common rectifier operation modes include constant voltage, constant current mode and constant potential mode [2, 7].

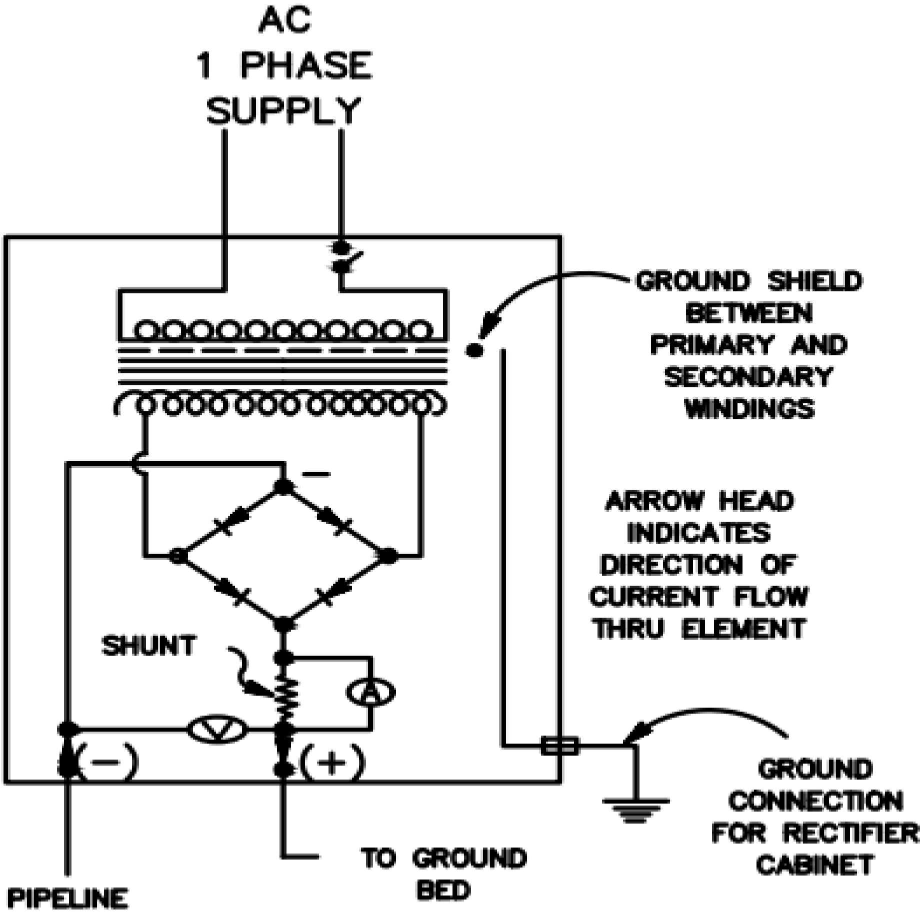


Figure 2.24: Single phase bridge rectifier circuit [2]

2.26 Impressed current ground bed installation

The location and the soil resistivity of the ground bed site need to be verified to confirm the design parameters. During construction, test results may require modifications in the design, e.g. anode depth, location, etc. These activities should be carried out by or in close co-operation with the design contractor of the ground bed.

Prior to installation, impressed current anodes need to be inspected for defects, conformance with the anode specification, size and length of anode cable tails to ensure that anode caps if used, are secure. Care must be exercised to avoid damaging anodes during handling and installation. Cable tails should be visually inspected for defects in insulation. Care must be taken to avoid damage to the cables or cable insulation. Each anode needs to be tagged with a unique code or number.

Anodes should never be handled, lifted or lowered using the anode cable, unless specifically allowed by the manufacturer in the installation instructions (e.g. stringed anodes). Impressed current anodes are usually installed in carbonaceous backfill. If the backfill material is supplied loose, it should be installed properly, so that there are no voids around the anodes. Anodes may also be delivered pre-packaged with compacted backfill in metal canisters [2, 31].

A hole of the specified diameter needs to be drilled to the required depth. All cuttings, mud and other foreign matter have to be removed from the borehole. A record needs to be kept of the drilling. The various layers, total depth and water level need to be recorded. A borehole resistivity profile needs to be made during drilling to confirm the boundaries of the low resistivity layers.

If specified, a casing needs to be set in the borehole. Normally a non-conductive (plastic) casing is used for the inactive length of the ground bed. Anodes need to be lowered on suspension ropes into the borehole to the specified depth. Anodes must not be handled using cable tails. Anodes need to be provided with centralisers to centre them and to prevent cable damage of lower anodes. The anode lead wires need to be permanently identified before installation.

If specified, a venting pipe perforated over the active length has to be installed along with the lower anode. If specified, slurry of carbonaceous backfill needs to be gradually poured or pumped into the borehole to the required depth, so that there are no voids around the anodes.

This may be done using a large diameter hose which is lowered down to the bottom of the hole and is retracted as the level of coke rises. The quantity of the backfill material needs to be recorded. The top of the borehole needs to be backfilled with graded soil or gravel to prevent cable isolation damage.

The anode cable tails needs to be terminated in the anode connection box and the headwork cover set in place. Care needs to be taken that anode cables have sufficient slack to cope with any backfill settlement. On completion of installation, the resistance of each anode to remote earth has to be measured and recorded using an Earth Resistivity Meter. These anode details should be recorded. After completion of the anode ground bed, the total ground bed resistance has to be measured and evaluated against the design [31, 38].

2.27 Field measurements

To ensure high performance or efficiency of the impressed current CP system, various testing techniques need to be performed on the structure under cathodic protection which is actually protected against corrosion. These various techniques involve the following:

- Structure-to-reference potential
- Surface potential measurements
- Soil resistivity
- Direct observation
- Test coupons.

These techniques are common means for determining if adequate protection has been achieved on the protected structure.

2.28 Structure-to-soil potential survey

This is a technique used to measure the potential difference between the metallic surface of the structure and the electrolyte that is measured with reference to an electrode in contact with the electrolyte. Its benefits are to locate stray current interference, anodic areas, coating defects and effectiveness of the CP system on the protected structure. Measurements are taken with a voltmeter connected in parallel in the circuit [2, 27].

The main aim of this measurement is to determine whether one of the cathodic protection criteria is met. Based on the NACE SP169 standard, voltage drop other than across the structure-to-electrolyte boundary must be considered to assess the effectiveness of a CP system using fixed potential measurements. Figure 2.25 illustrates the structure-to-soil potential profile measurement using a DC voltmeter [2].

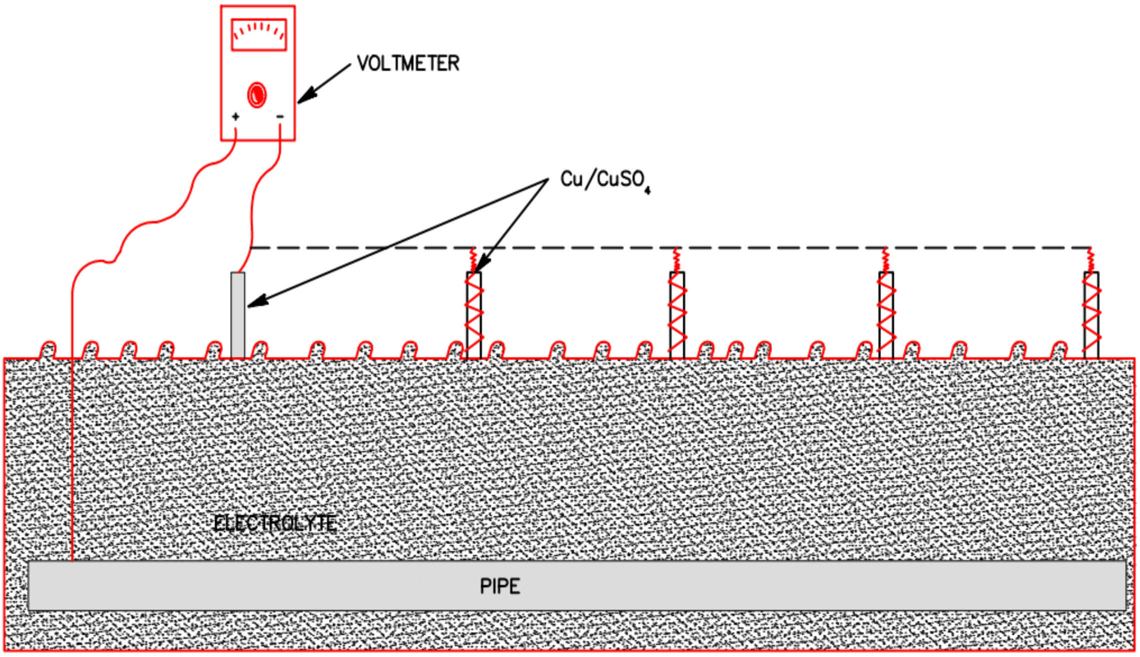


Figure 2.25: Structure potential profile measurement using DC Voltmeter [2]

2.29 External coupons

Installation of external cathodic protection coupons is another method or technique utilised to monitor or simulate whether the protected structure complies with cathodic protection criteria and provides evidence that the CP system is working. They are weighted and connected to the protected structure. Coupons are installed in combination with a potential monitoring test posts.

They are installed at structure depth in the backfill as the structure where they receive the same exposure to cathodic protection current. After a known exposure duration, they are removed and weighed. Corrosion rate is the weight loss per time unit. External coupons receive cathodic protection current and represent the structure at the test post or station [31].

To measure the instant OFF structure of a soil potential survey, the coupon is momentarily disconnected from the structure via an interruption switch connected in series with the coupon and its potential with respect to the electrolyte is recorded or measured. This measured value is essentially an IR drop free reading of the coupon potential to the reference electrode. The IR drop potential of the coupon is similar to the instant off potential of the underground structure. If the coupons comply with the CP structure polarisation criteria, then it is inferred that the protected structure would also meet this criteria [2, 27].

The benefits of utilising coupons on the impressed current CP system are that IR drop free potentials can be obtained without interrupting multiple power sources, structure-to-reference potentials can be measured on the structure with directly connected galvanic anodes, and depolarisation tests can be done on the structure without de-energising the CP system [31]. Figure 2.26 shows how a coupon is connected and instant OFF recordings are measured.

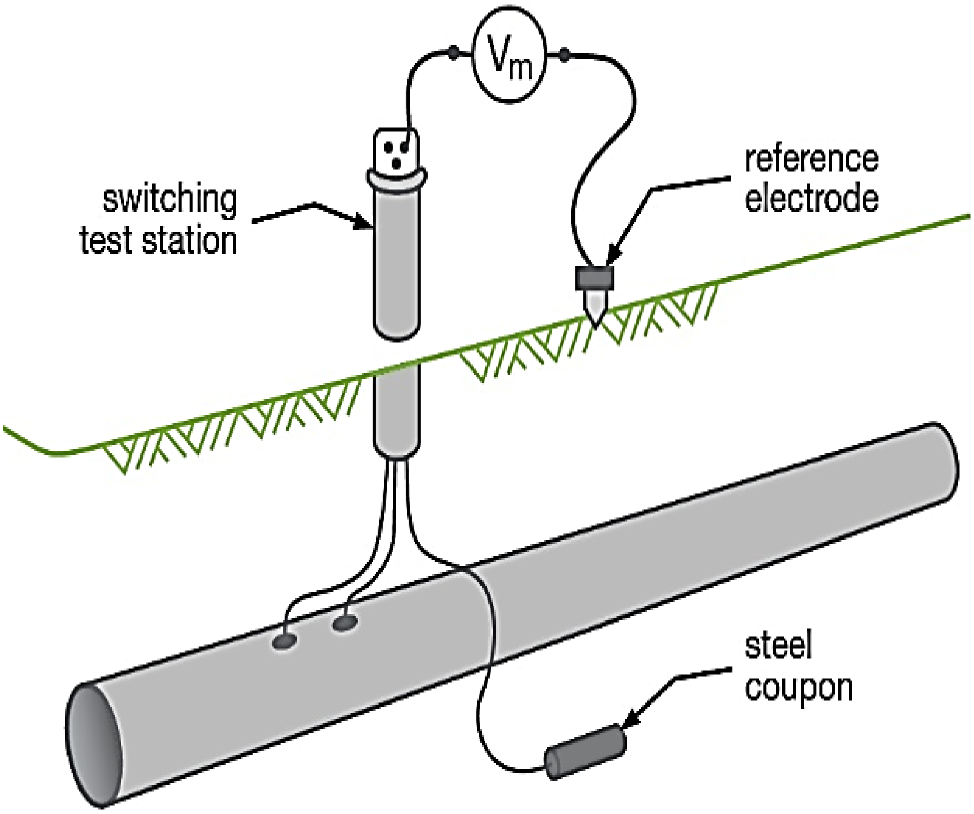


Figure 2.26: Instant OFF potential simulation using external steel coupons [2]

Figure 2.27 is a graphical representation showing structure depolarisation potential decay during instant OFF potential being tested after the structure has been full-polarised [2].

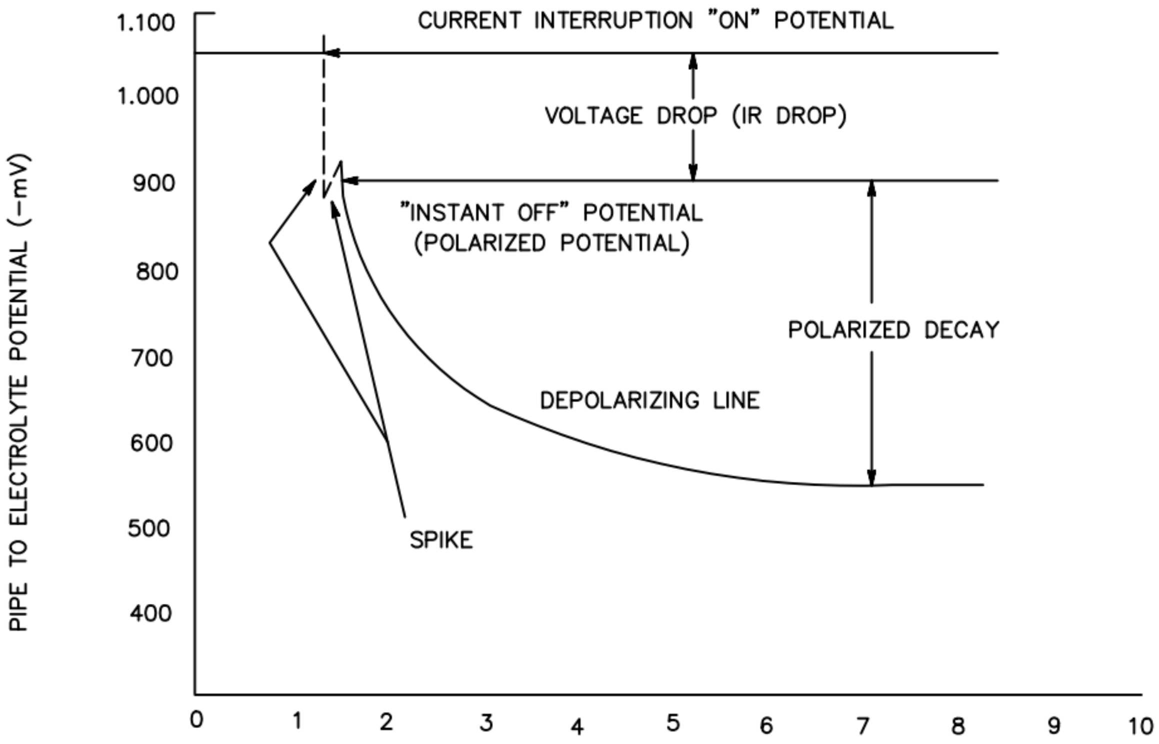


Figure 2.27: Structure depolarisation potential decay curve [2]

2.30 Surface potential survey

Surface surveys are utilised for many purposes including a structure-to-soil potentials profile, coating defects location, size and to determine if a NACE criterion for CP is met. These surface surveys involve close interval potential (CIP) and a direct current voltage gradient (DCVG) survey.

Since these surveys are usually used to determine if the criterion for CP is met, the recordings must be IR drop free and sufficient recordings must be taken to be confident that a representative number of areas have been tested to provide an accurate picture of the status of protection through the structure. The potentials should be taken at intervals close enough to provide a clear understanding of the status of protection. For areas where potentials may vary quickly along a structure or pipeline, a close interval potential survey should be performed [2].

2.31 Close interval potential survey

Potential measurements at key pipeline test posts are a good indication of the general protection levels of a pipeline. However, it is possible that in the areas between test posts, there are locations where coating damages exist that are not fully protected. To detect such locations, a close interval potential survey (CIPS) can be carried out which basically consists of ON&OFF potential measurements every one or two metres. Contact with the pipeline is made in the nearest test post or other accessible location via a trailing wire.

During the survey, the transformer rectifiers are interrupted in synchronisation. Many systems are computer controlled and take the readings synchronised with the rectifier interrupters. Some modern interrupters use either radio timing signals or GPS [25, 27].

Sometimes, it is necessary to measure the pipe-to-soil potential at a fixed point as well to detect time dependent variations (such as stray currents) that might be mistaken for localised defects. The measurements are usually presented in graphical form together with pipeline features (crossings, fittings) that can serve as a reference point to relocate the defects. By means of this technique, those defects that are under protected can be listed for repairs [25].

The principle of a close-interval potential survey (CIPS or CIS) is to record the pipe-to-soil (P/S) potential profile of a pipeline over its entire length by measuring potentials at intervals that do not significantly exceed the depth of the pipe (often ± 1m). The CIS survey obtains structure-to-electrolyte potentials at relatively short intervals along the structure such as at 1m (3ft) to 3m (10ft) spacing [30].

The CIPS technique provides a complete P/S potential profile, indicating the status of CP levels, to evaluate the criteria for the cathodic protection system, to identify local deficiencies in a cathodic protection system, and to aid in determining the requirements to enhance the level of cathodic protection the level of CP to the structure.

The interpretation of results, including the identification of defects, is relatively straightforward. The most useful graphical presentation of CIPS data is plot the “ON” and “OFF” potentials together as separate profile versus distance [25].

A series of structure-to-electrolyte potential determine if adequate cathodic protection is achieved at all points along the structure, as illustrated in Figure 2.28 [25].

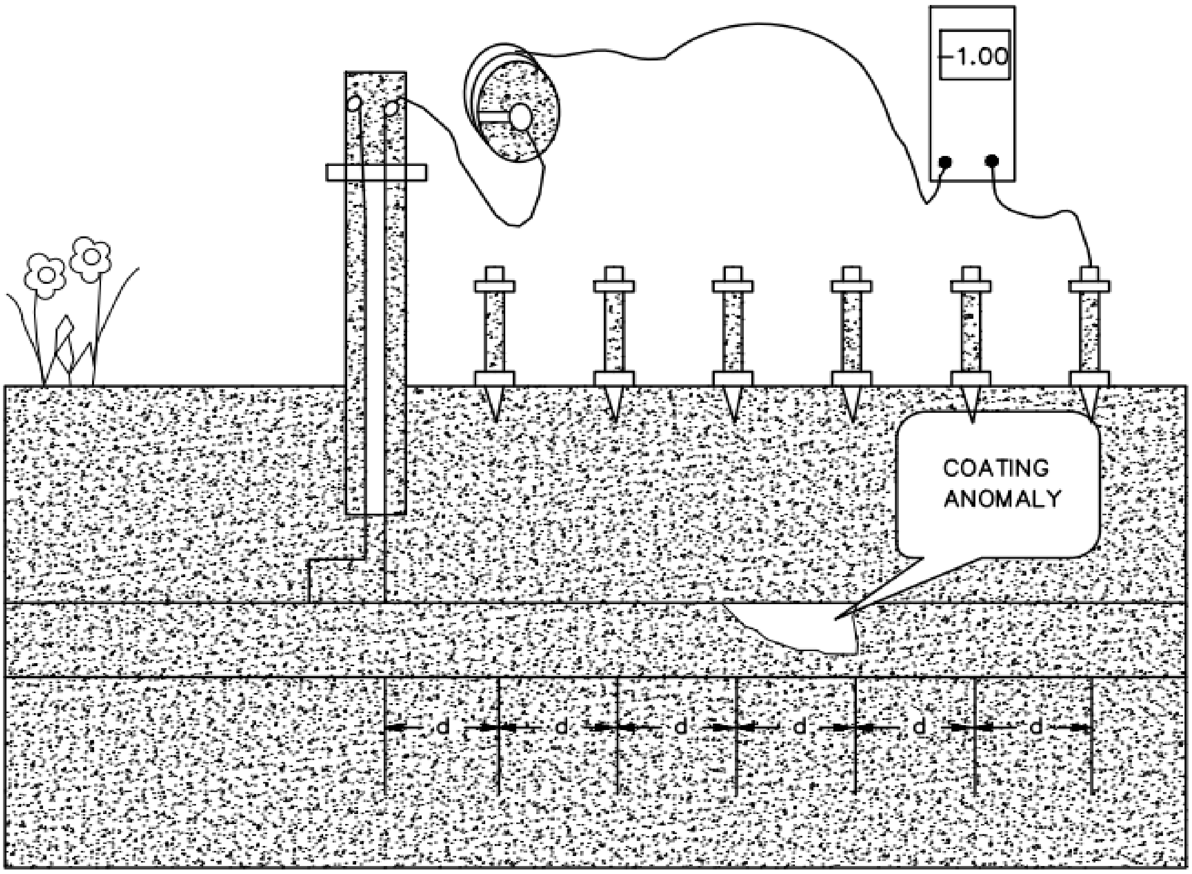


Figure 2.28: Close interval potential profile measurement circuit [25]

2.32 Direct current voltage gradient survey

Direct current voltage gradient (DCVG) is a technique that detects the potential gradients in the soil generated by the cathodic protection system. By means of two reference electrodes, the direction of the (interrupted) cathodic protection current can be detected and leads the surveyor to the coating defects. The exact location is determined and pegged. The relative signal strength is indicative of the relative size of the defect (i.e. as % IR). This technique also works on parallel pipelines. Combining methods can let the surveyor both measure the level of cathodic protection and determine the presence of coating faults and their severity [34].

When cathodic protection current flows through the soil to a coating defect on a pipeline, a voltage gradient is established in the ground due to the resistive nature of the soil. From Ohms' law, this voltage gradient will be higher in high resistivity soils. The DCVG techniques utilise a sensitive millivolt meter to measure the voltage difference between two copper sulphates half-cells (probes) placed in the soil voltage gradient region. Figure 2.29 shows a typical survey method of DCVG+CIPS [34].

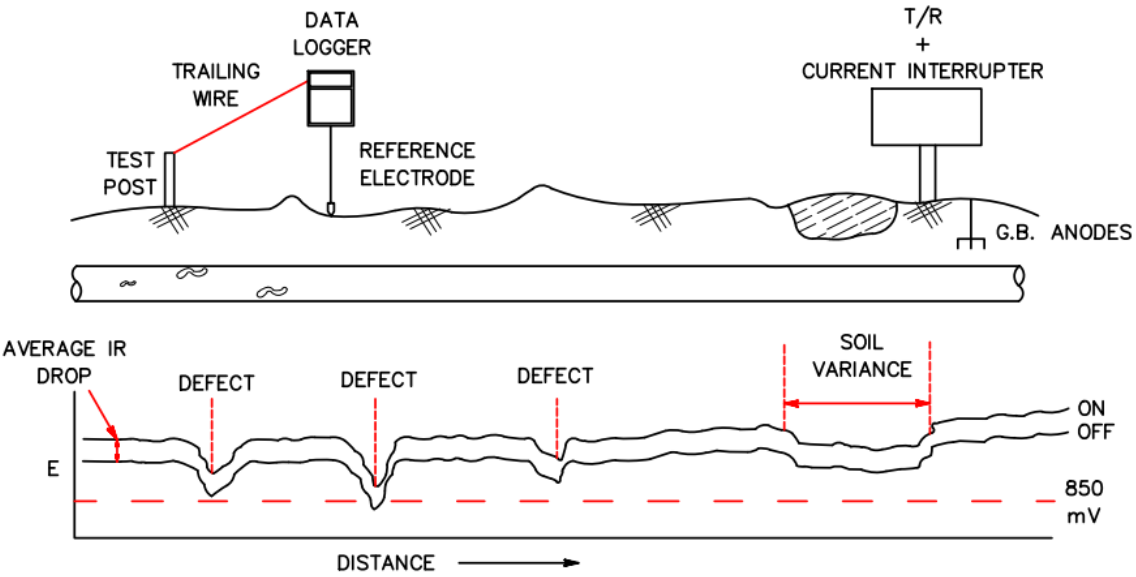


Figure 2.29: Typical combined CIPS and DCVG survey connection diagram [34]

2.33 Soil resistivity survey

The main aim of this survey is to determine the resistivity of an electrolyte either by a Wenner four-pin method or by a soil box. The lower the resistivity, the higher will be the corrosivity. Sandy soils are high up on the resistivity scale and therefore considered the least corrosive while clay soils are excellent at retaining water and at the opposite end of the corrosivity spectrum [25].

Soil resistivity measurements are important both in the prediction of a corrosive electrolyte and in the design of impressed current cathodic protection systems. Based on this investigation, a four-pin method was used. Field soil resistivity measurements are most often conducted using the Wenner four-pin method and a soil resistance meter following the principles laid out by Wenner [25].

The Wenner method requires the use of electrodes and place on equidistance as shown on Figure 2.30. The typical probes spacing is in increments of 0.5 to 1m. Note that the four-pin test measures the soil resistivity to an average depth that is the same as the spacing between the two inside pins. The results of soil resistivity then computed from the instrument readings and calculated using formula [25].

$$\rho = 2\pi aR$$

Where ρ is the soil resistivity (Ω-cm)

a is the distance between probes (cm)

R is the soil resistance (Ω), instrument reading

π is 3.1416

Measured soil resistivity test results obtained from Wenner four-pin testing indicate the average soil resistivity from the earth surface down to depth. A factor must be determined to convert a resistance measurement in Ohms to resistivity in Ohm-centimetres. The direct current (DC) four-pin soil resistivity test with equal spacing is shown in Figure 2.30 [25].

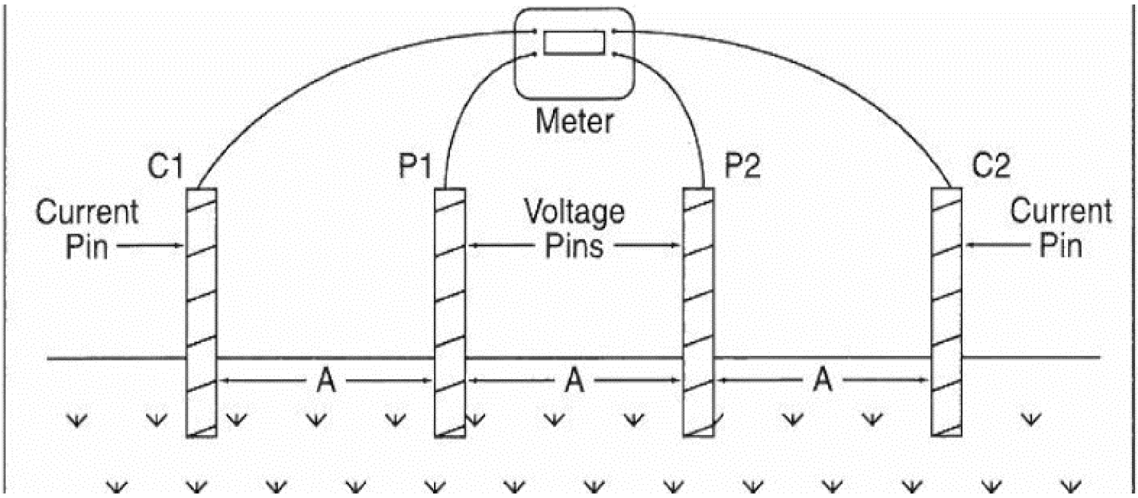


Figure 2.30: Four pin soil resistivity test with equal spacing [25]

2.34 Stray currents

Stray currents are returning currents from large direct-current systems, employing an earth or with an uninsulated return path, that do not form part of the affected structure. Stray currents interfere with buried (or submerged) metal structures by flowing from the soil into the structure in one location and flowing from the structure into the soil in another location.

The stray current uses the structure metal as a preferential low resistance return path. In the locations where the current flows from the metal into the soil, anodic currents may cause accelerated corrosion. Sources of stray currents can be own or foreign cathodic protection systems. DC railway or tramway traction, welding generators, and DC power systems [27].

There are alternating and direct current stray currents, but the DC stray current causes more corrosion in most of metals. In some locations such as rail rapid-transit systems, underground railroads pipelines may carry hundreds of amperes of stray currents. If stray current is not controlled, it can cause defects on the structures that can grow faster and destroy the structure depending on the amount of stray current discharge from the structure.

The main objective of this survey is to determine the source of stray current, where it enters and leave the structure, its magnitude and mitigation. Dynamic stray currents vary in amplitude and change direction of current flow and can be man-made [36].

2.35 Stray current from traction systems

The returning currents from DC traction systems may be partly conducted by the soil back to the substation. This effect is larger when the resistance of the tracks is high and/or the isolation between tracks and the soil is poor or absent. The current can cause stray currents on pipelines running more or less parallel to the railway. The current enters the pipeline at coating damages between the location of the train and the substation and the current leaves the pipeline usually close to the substation where it can cause severe corrosion.

As the stray currents are intermittent, depending on the rail traffic, they are difficult to detect. Light stray currents can sometimes be conducted back to the tracks by resistance and diode bonding. If the exit point of the current is known, zinc or other low resistance earthing blocks can be used to provide an exit point to earth. However, this needs to be monitored over time to ensure complete depletion does not occur. Severe stray currents have to be mitigated by potential controlled rectifiers of sufficient capacity and reaction time, placed in the vicinity of the points where the stray currents leave the steel to re-enter the soil [29].

The main consideration is that the steel-to-soil potential should be as uniform as possible over the whole of the protected structure or pipeline. Where these points are near the railway, the rectifier can be connected directly to the railway. This will make cathodic protection possible, as it considerably reduces effects of peaks in the stray current exit to earth [2] . Figure 2.31 shows the direction of stray current caused by traction system.

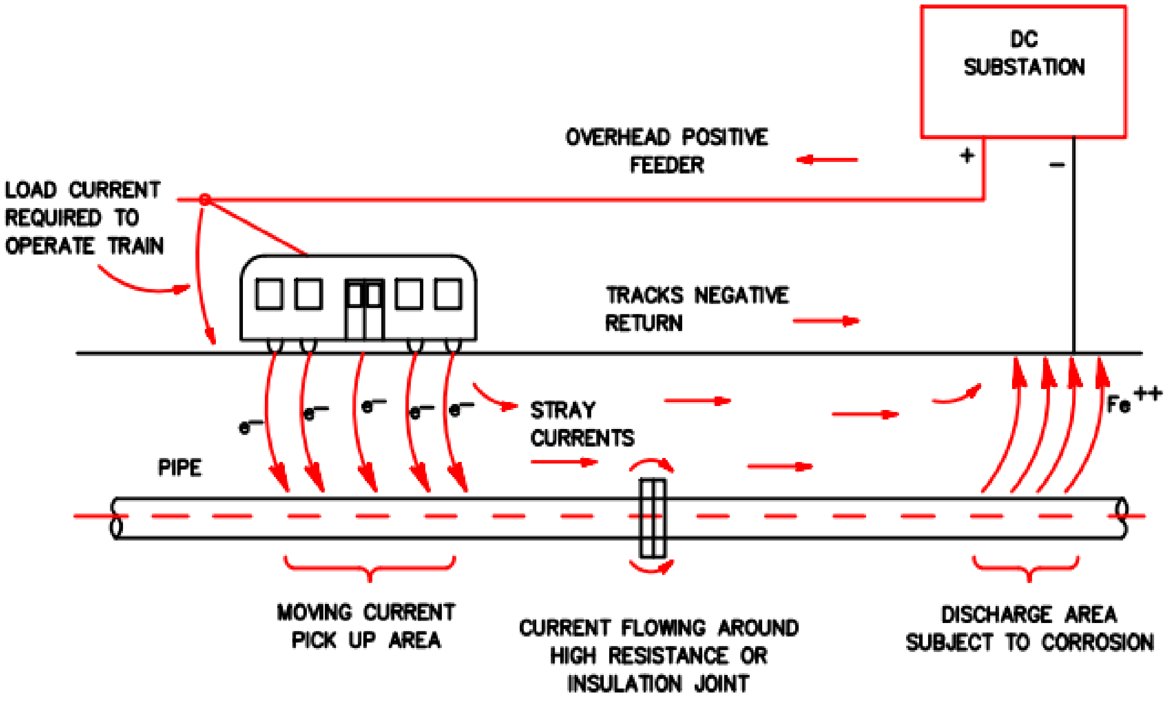


Figure 2.31: Stray current caused by traction system [1]

2.36 Detection of presence of stray currents

Detection of stray current interactions is usually carried out on the basis of potential. The structure potential value and its variability are adopted as criteria of the electrolytic corrosion hazard. The potential of a structure measured versus the reference electrode has a constant value when no current stray currents are present, and this is called stationary potential.

The potential of the structure dramatically changes in the regions of occurrence of stray currents as the result of induced polarisation, which is random in character. Changes can take place in a positive as well as negative direction in relation to the stationary potential. Thus, on the basis of a field potential measurement of a structure and variations of the measured signal, one can deduce the presence of stray currents [38, 39].

The other symptoms of the structure that is affected by the stray current are localised pitting in locations near to a foreign structure, breakdown of protective coatings in a localised area near to a foreign anode ground bed or other sources of stray direct current and structure-to-electrolyte potential profiles that indicate abnormal variation from a previous survey. Installing mitigation bond in the area where the structure tends to discharge stay current is one of the effective techniques to minimise stray current. This is done by measuring the maximum current flow through the proposed bond.

The potential measurement can be performed with a voltage meter of high internal resistance (minimum 100 kΩ/V). One of the outputs of the meter is connected to the structure with a cable. The second input of the meter is connected to the reference electrode, which is placed on the surface of the ground as near the structure as possible. The copper sulphate reference electrode is used most frequently in field conditions. Nowadays, microprocessor digital voltmeters, digital recorders are commonly used [39] .

2.37 Isolated flanges

Isolation flanges need to be installed on the underground pipelines to block cathodic protection to pass to the area of the pipelines that is above the ground. This may be necessary when retrofitting cathodic protection onto existing pipelines or piping. Isolated flanges are standard ANSI type flanges provided with a special isolating gasket and isolating sleeves and washers for the isolation of the bolts. Figure 2.32 is a schematic drawing of the flange [2].

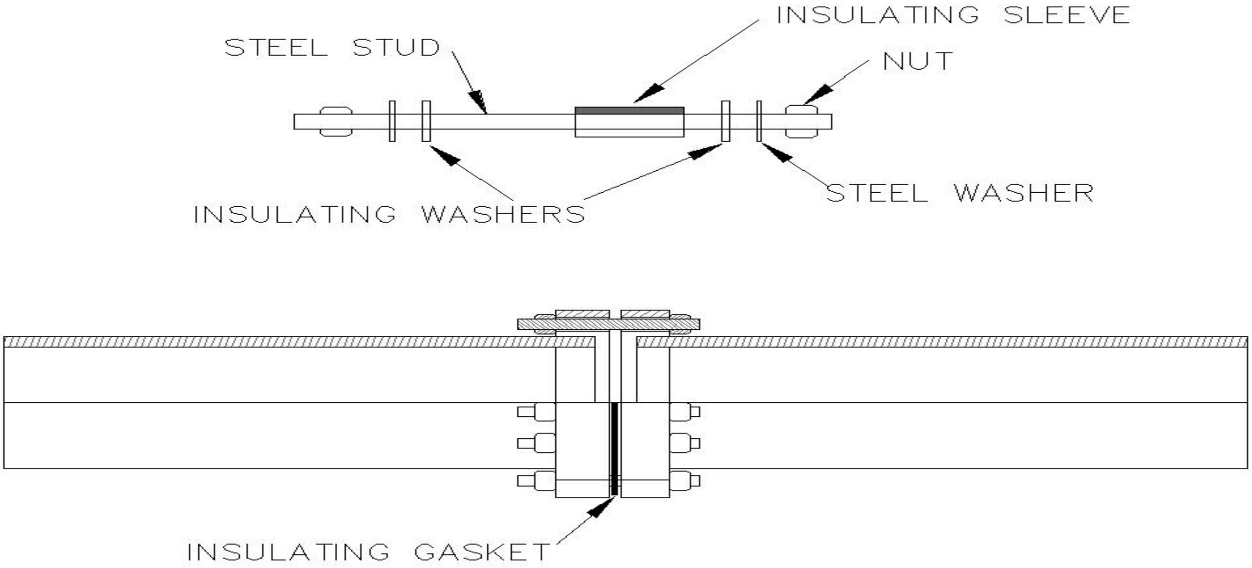


Figure 2.32: Typical schematic for isolation flange [2]

Chapter 3: Research Design and Methodology

3.1 Introduction

To achieve the main objective of determining whether impressed current cathodic protection (ICCP) is an effective CP system for protecting the underground pipelines carrying petrochemical products, different data collection and analysis techniques were selected to be the most suitable for this type of study and were implemented. The ethical consideration compliance requirements were followed and are presented in Appendix A.

To ensure validity, during the field survey, two sets of meters were employed on each test and testing instruments' calibration certificates were obtained in advance.

3.2 Study flow chart

Figure 3.1 is a study flow diagram showing the process for conducting this study, including the data collection methodology process.

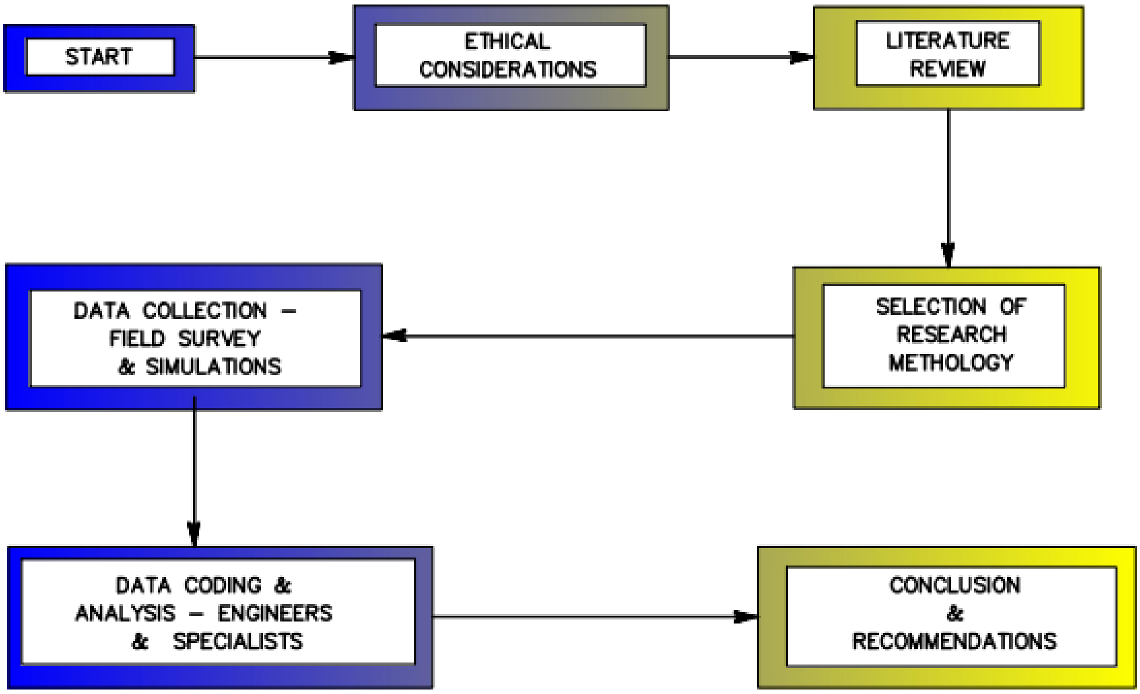


Figure 3.1 Study flow diagram

All the surveys for this research were done twice for reliability. The first collection of data is referred to as the baseline survey and the second collection of data collected is referred to as the post survey data. These surveys included but were not limited to ON pipe-to-soil spot potential, ON and instant OFF pipe-to-soil spot potentials, anode ground bed performance, transformer rectifier unit performance, integrity of pipelines isolation flanges, stray current, CIPS & DCVG, and cross bonds between the pipes. The data collection strategy comprised three parts: visual inspection, field measurement, and simulations.

Since Engen is a national key point and hazardous area, a letter of consent was sent to the Electrical Department Manager as part of ethical considerations requesting a permit approval to utilise Engen Refinery for conducting this study. The content of the letter and statement of agreement included, among other aspects, the study purpose and procedure, risk involved confidentiality issues, HSE issues, conduct etc.

3.3 Research methodology

Based on the literature reviewed, the researcher identified the following data collection approach to be suitable for this study:

- Field observation and testing
- Field simulation
- Visual inspection

This data collection methodology was employed to gain first-hand knowledge to support or validate information gained from the literature review. The surveys were all performed on eight Engen underground transfer lines system. The recorded data was coded into numerical, tables, pictures and graphical form, to measure the relationship between the variables and for analysis purpose.

3.4 Pipe-to-soil spot potential survey

A combination of the reference electrode and data loggers was utilised in most of the surface structure-to-electrolyte potential surveys. Structure-to-soil potential was conducted to determine if the adequate cathodic protection had been achieved.

The data was collected with the voltmeter connected in parallel on the circuit. This test was performed in all transfer lines test posts and the instruments used were a TBM811XEX intrinsically Safety DMM data Logger (A) installed in each test post and a portable copper sulphate reference electrode (B), as shown in Figure 3.2.

The recordings were performed as per NACE SP169 standard requirements. Figure 3.2 includes the testing equipment used for the pipe-to-soil ON spot potential survey along the Engen petroleum transfer pipelines and the Multimeter data logger & copper sulphate reference electrode.

(A) (B)

Figure 3.2: Multimeter (A) and copper sulphate reference electrode (B)

Figure 3.3 is diagram illustrating the pipe to soil spot potential recordings circuit that was utilised to check transfer lines' potential profile [2].

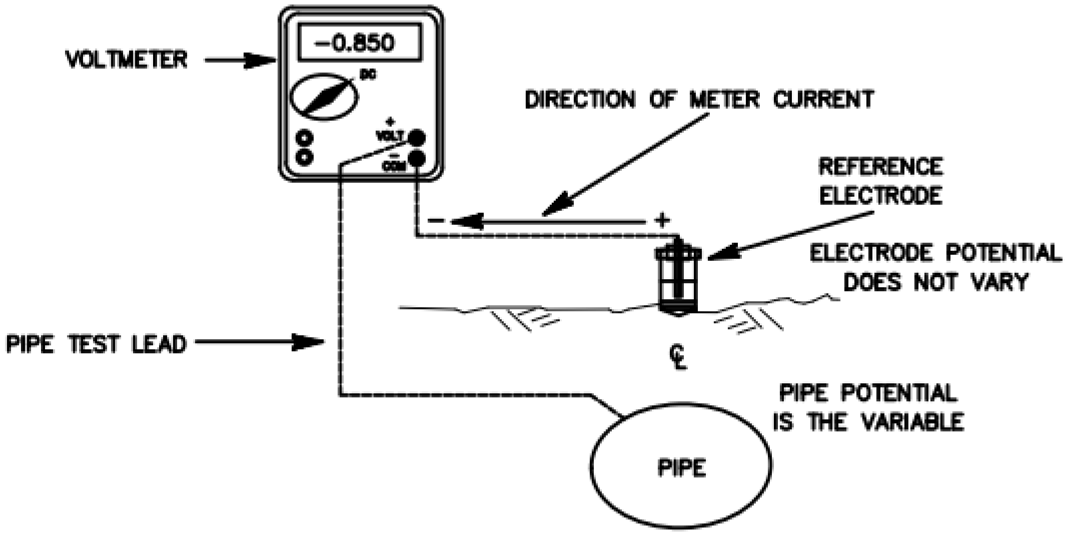


Figure 3.3: Pipe to soil spot potential recordings circuit diagram [2]

Figure 3.4 shows how the ON spot pipe-to-soil potential was being done on all transfer lines' cathodic protection test posts.

Figure 3.4: Volt reading on meter for pipe to soil potential in Engen TPs

3.5 Stray current survey

Stray currents are detected by monitoring the pipe-to-soil potential over a 24-hour period. Current entering or leaving the pipeline causes variations in the pipe/soil potential, which indicates the direction and intensity of the current.

The same data collection technique and equipment were utilised for stray current data capturing as for the “ON” pipe-to-soil spot potential survey. The difference is that a stray current is recorder on the 24-hour period and spot potential is recorded for a minute by the same instrument and circuit. A combination of permanent copper sulphate reference electrodes and TBM811XEX intrinsically Safety DMM data Loggers installed in all cathodic protection test posts were utilised in conducting the stray current survey in the entire pipeline system.

These pipe-to-soil potential recordings were made over 24hours for every minute in order to ensure representative results, as traction movements vary considerably over a 24hr period. The main objective of performing this survey was to determine the source, magnitude, where and at what areas the structure enters, where and at what areas the structure leaves, and how it can be mitigated.

All the data loggers were calibrated before conducting the tests. For the analysis, variables from one point on the pipe to another were compared. Stray current is detected by pipe-to-soil potentials that are changing with time with the reference electrode in the stationary position in contact with the electrolyte. Figure 3.5 is a graphical representation of how DC stray current moves from the rail back to its source and at which locations, where there is a possibility of corrosion, that the current leaves the structure.

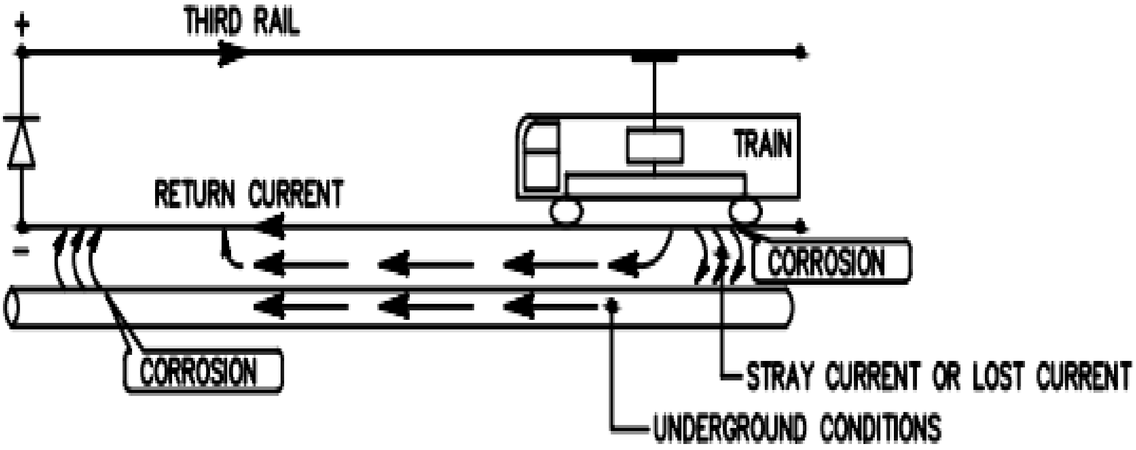


Figure 3.5: DC stray current flowing back to source via pipeline [36]

3.6 Combination of CIPS and DCVG survey

The direct current voltage gradient (DCVG) survey was performed on the entire cathodic protection pipeline system. It is a data collection method for detecting coating defects. Close interval potential survey (CIPS) is a data collecting technique to determine if adequate cathodic protection is achieved at all points along the underground pipelines.

In a close interval survey, the structure-to-electrolyte potentials data were collected at close spacing (1 to 5 m). This was done by carrying a voltmeter of data logger and a wire-dispensing device.

The combination of testing instruments that were used to conduct this survey were the RGT4400GPS Timing Source, (GPS Antenna, frequency:1575, Voltage:3V-5V SGS FC CE) Corrosion Control Interrogator and RTS Precision Timer Switch as shown in Figure 3.6.

The survey was conducted using a combined recording direct current voltage gradient and close interval potential survey. The applied cathodic protection current was interrupted allowing for the measurement of “ON” and instant “OFF” potentials using copper/copper sulphate reference electrodes. These potentials’ readings were recorded by synchronised static and mobile devices.

A trailing cable provides a connection to the pipe and was used for distance measurement. The survey was conducted using 2.4 seconds “ON” and 0.6 seconds “OFF” timing achieved by using a switching unit synchronised to the mobile and static devices. The transfer lines were surveyed collectively as a common cathode.

All the TRUs at different locations were switched on (Travancore, Checkers, Swamp and Travancore area). The cross bonds at all the test posts along the route were disconnected to avoid the interference with the foreign pipes. The survey was conducted as close as possible to exactly above the pipe. Where the surface above the pipeline is hard paved the survey was conducted on the nearest unpaved surface.

The CP system was reinstated during any extended breaks in the survey as well as at the end of each day to ensure that the pipe did not depolarise, and that the integrity of the CP was maintained.

Figure 3.6: CIPS and DCVG testing equipment

Figure 3.7 is an example of a DCVG survey circuit diagram showing how the defects are being identified. And Figure 3.8 is an example of CIP survey connection circuit.

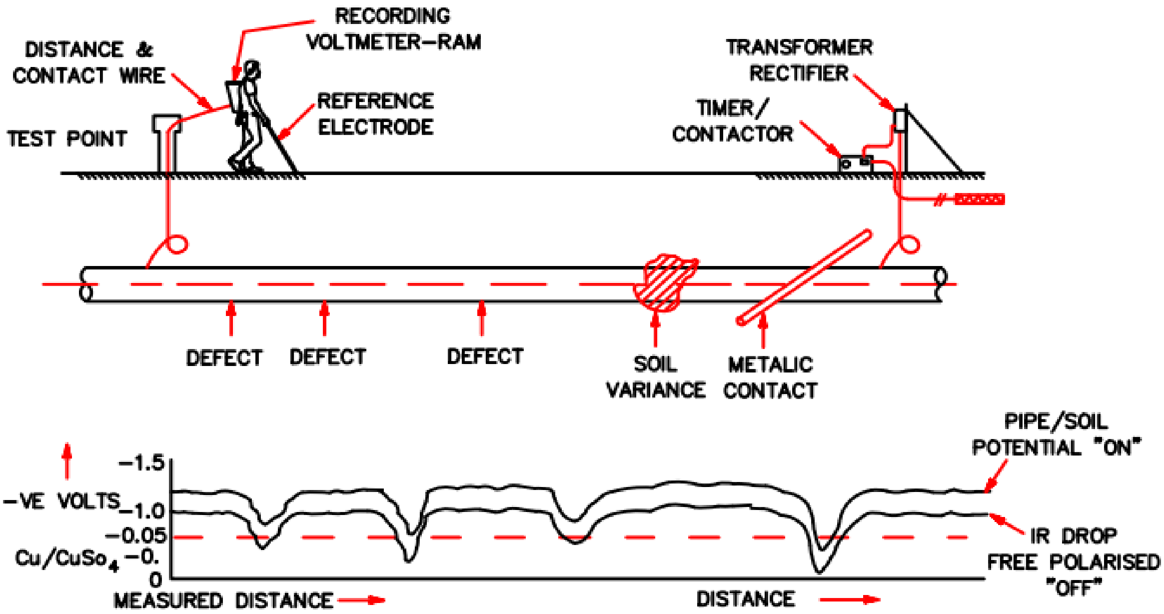


Figure 3.7: Example of DCVG survey circuit diagram [25]

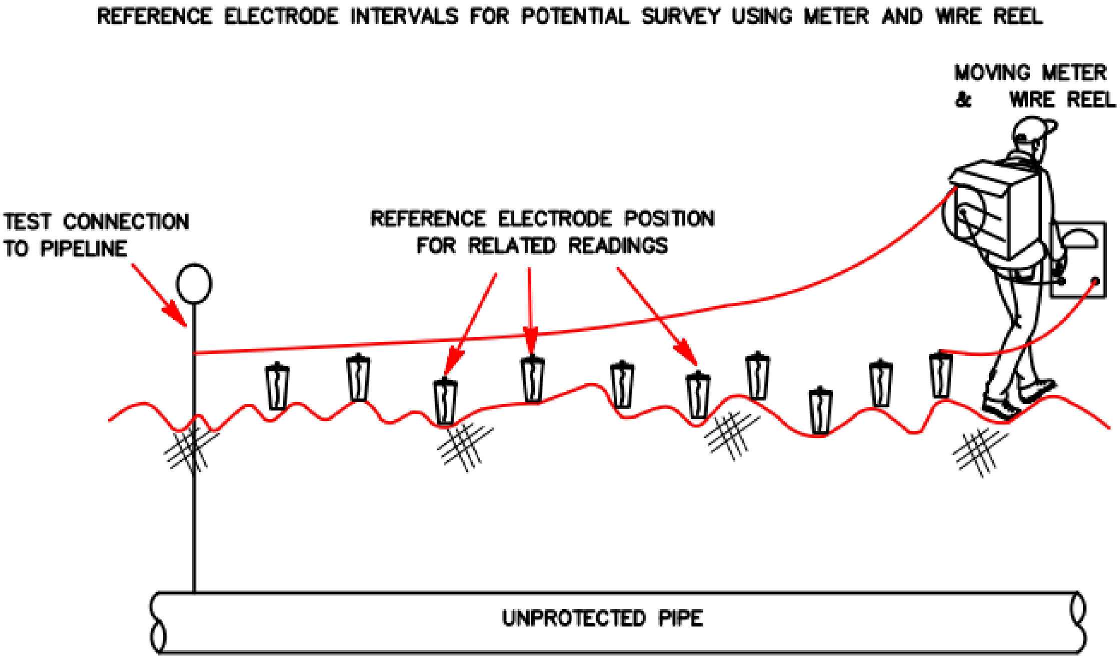


Figure 3.8: Example of CIP survey connection circuit diagram [25]

3.7 Transformer rectifier output survey

This survey was conducted in all transfer lines’ transformer rectifier units (TRU) to check the CP system current demand, TRU performance and anode ground bed efficiency in terms of the resistance, as per the literature review information. Fluke 177 DMM was used on the DC scale during TRU output current and voltage terminals’ data recordings.

An anode ground bed resistance was estimated using Ohms Law (V=IR) equation based on the TRU output current and voltage recorded values. Collected data was saved in a computer spreadsheet for the analysis. Figure 3.9 shows how the TRU output voltage and current were being measured. Figure 3.10 is a diagram of a transformer rectifier unit test circuit that was used for the out recordings.

Figure 3.9: TRU output recordings

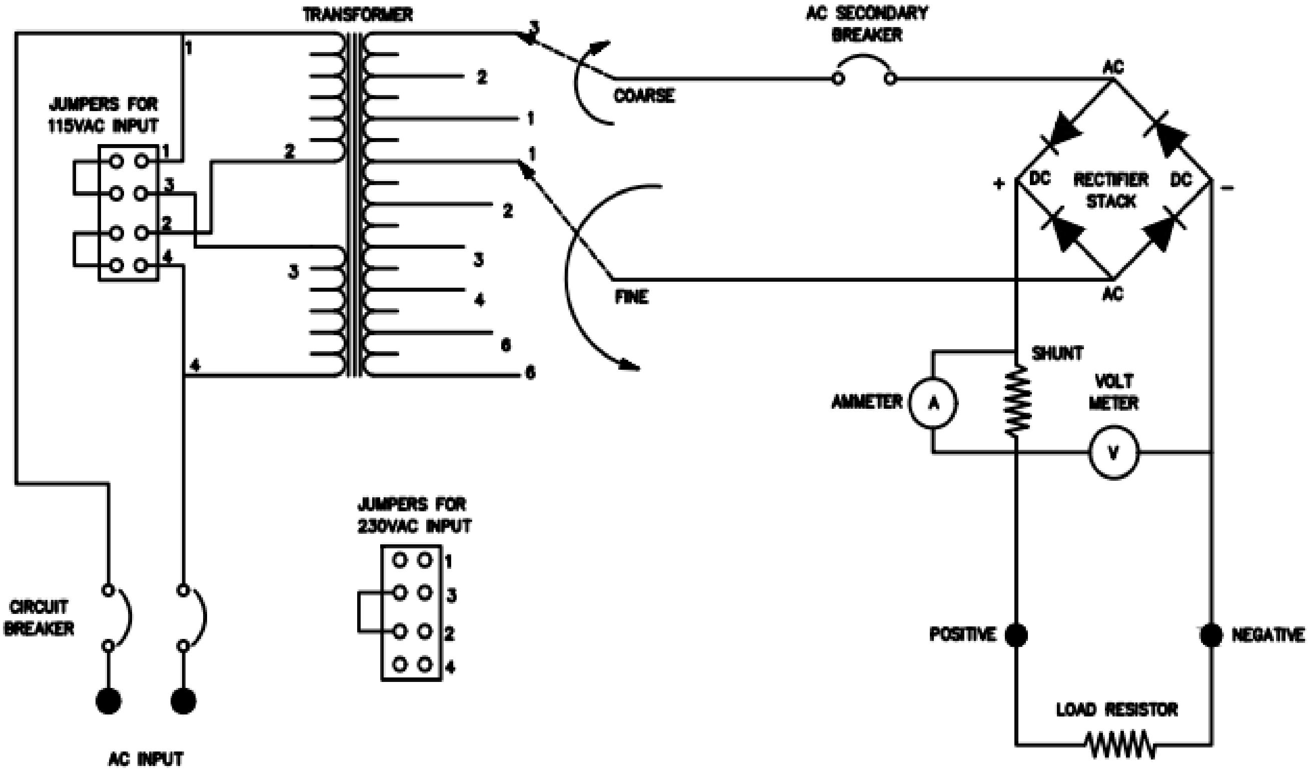


Figure 3.10: Transformer rectifier unit test circuit diagram [2]

3.8 Electrical isolation flanges

This survey was performed on the transfer lines' isolation flanges to check the integrity of isolation flanges. This is another data collection method of ensuring that the CP system does not fail to maintain a satisfactory level of cathodic protection due to being short on isolation flanges.

The test equipment utilised to conduct this survey comprised the Tinker & Rasor MODELRF-IT Radio Frequency Isolator Test and the TBM811XEX data Logger just for comparisons. The insulation checker uses a radio frequency skin effect and only reads the immediate joint to determine insolating flange effectiveness. The insulation checker operates by placing two prongs in contact with the insulating joint, one lead on each side of the insulating element.

The instrument identifies the shorted flanges, detects shorted bolt-sleeve-washer assemblies or the not shorted condition of the joint but this instrument does not indicate the resistance of the joint. With the Fluke meter it shows the values of resistance or voltage depending on the scale on the selector switch.

The isolator tester probes are placed in contact with each side of the flange. A functioning electrical isolation flange will show a full-scale deflection while an electrically shorted flange will show a deflection toward zero on the scale. Figure 3.11 is a Tinker & Rasor MODEL RF-IT Radio Frequency Isolator Test. Figure 3.12 illustrates the isolation flange integrity testing circuit using the Fluke 177 meter. Figure 3.13 illustrates the field connection of transfer lines' isolation flange integrity testing facility.

Figure 3.11: Tinker & Rasor Model RF-IT Isolator Tester

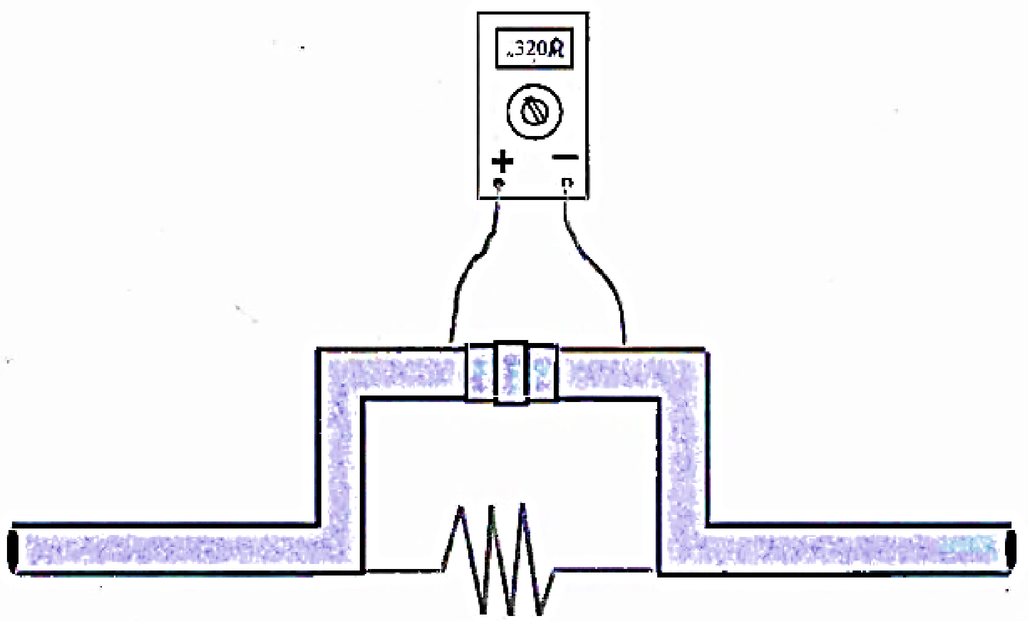


Figure 3.12: Isolation flange integrity testing circuit diagram

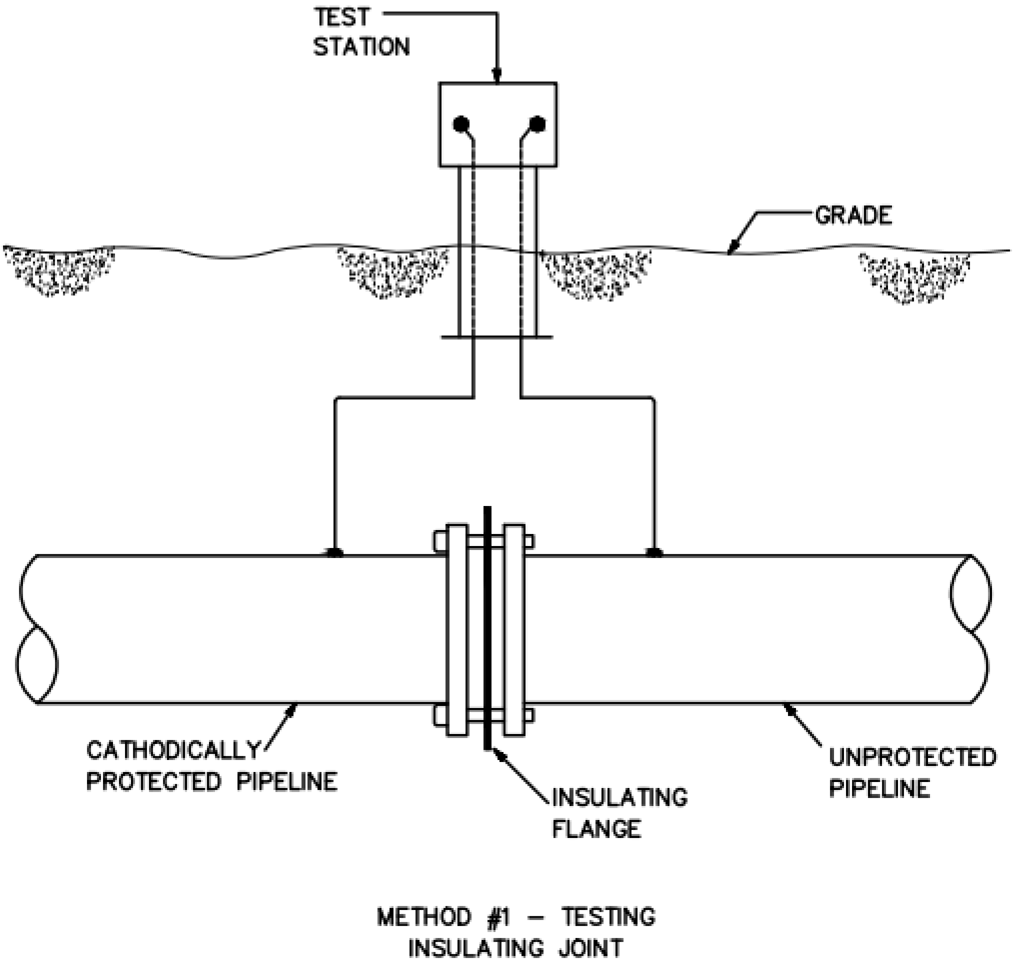


Figure 3.13: Transfer lines' field isolation flange testing facility connections [27]

3.9 Soil resistivity survey

The aim of conducting this survey along the pipelines was to gauge the status of the effectiveness of soil resistance around the anode ground bed locations. The measuring tool or instrument that was utilised was the ABEM TERRAMETER SAS 1000/4000. The pin array was at 5 m.

Figure 3.14 is a picture of ABEM TERRAMETER SAS 1000/4000 testing equipment that was used to conduct this survey. Figure 3.15 is a diagram representing a soil resistivity test connection circuit. Outer pins are for current measurement and inner pins are for voltage measurement. Results were saved in the testing instrument and plotted for analysis.

Figure 3.14: ABEM TERRAMETER SAS 1000/4000

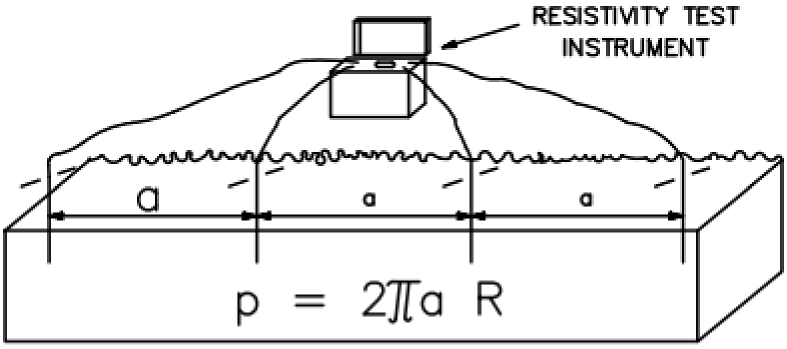


Figure 3.15: Soil resistivity test connection circuit diagram [27]

3.13 Field simulation

3.13.1 Structure cathodic protection polarisation criteria field simulation

External coupons were used to verify the pipelines’ cathodic protection polarisation criteria compliance. For data collection, coupons and permanent reference electrodes were installed at the same depth as the pipe to check whether underground pipelines comply with the 100 mV “ON” and -850 mV instant OFF cathodic protection structure polarisation SP0169 NACE criteria.

Coupons and permanent reference electrodes were installed in some of the cathodic protection test posts along the transfer lines for simulation purposes. A cathodic protection coupon is a metal sample representing the pipeline at the test site, used for cathodic protection testing, and having a chemical composition approximately that of the pipe. The coupon size is small to avoid excessive current drain on the cathodic protection system**.**

It is electrically connected to the protected pipes via a switch. The main objective is to monitor cathodic protection levels on the pipelines. Data capturing was conducted using the TBM811XEX data Logger permanent reference electrodes by performing a “ON” and instant “OFF” pipe-to-soil potential survey by interrupting the coupon switch.

It is another technique to check the effectiveness of the CP system. Recorded data was saved in the computer spreadsheet for analysis purposes. Figure 3.16 is a diagram showing the connection in one of the transfer lines test post on how Instant OFF potential simulation recordings using coupon data was captured.

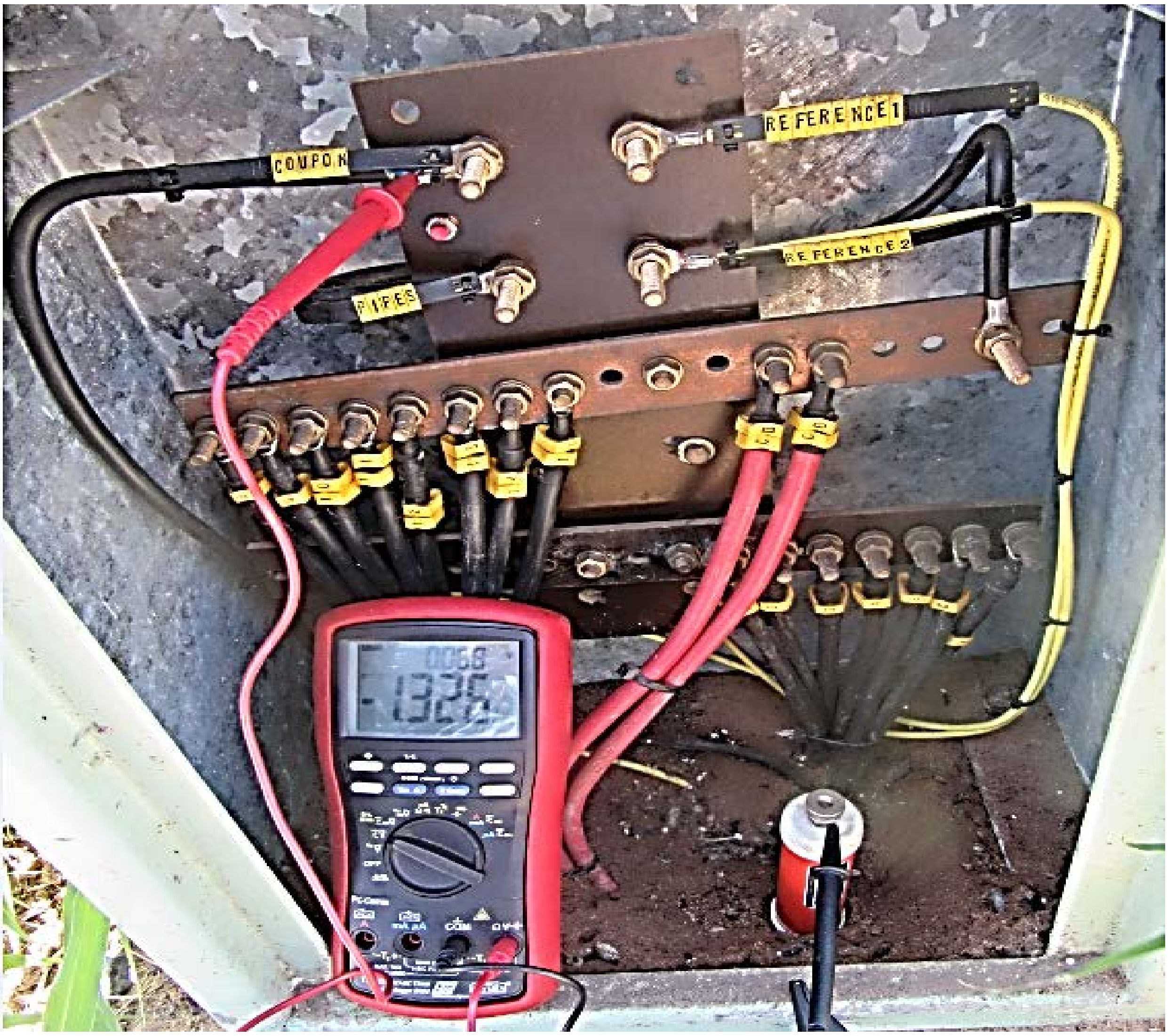


Figure 3.16: Example of instant OFF potential survey using external coupon

Chapter 4: Results and Discussion

4.1 Introduction

This chapter analyses the research findings based on the data recorded from the visual inspection, field simulation and surveys on the Engen transfer lines' CP system. Different effective and recommended surveys by NACE SP0169 were used systematically to fulfill this study's main objectives. The results of this study are presented graphically and in table format to enable presenting the analyses that the researcher conducted. The results include both baseline and post surveys for the study.

4.2 Pipe-to-soil "ON" spot potential results

Potential measurements are a common means of determining if adequate protection has been achieved. With the application of current from the environment onto a structure, a potential change with respect to the environment will occur. The potential change is a reflection of polarisation. Measurements are made to determine whether one of the CP criteria is met.

The ON spot potentials at the test posts along Engen transfer lines were recorded. The data logger was on a DC voltage scale. The positive lead connected to the structure and negative lead connected to the reference electrode to capture the correct readings. Baseline and post survey results for structure-to-electrolyte "ON" spot potential results are summarised in Table 4.1.

Figure 4.1 shows the route where the research was performed on Engen Petroleum Refinery. Cathodic protection surveys were performed on Engen transfer lines between Engen Refinery and Bluff Meat Supply along Tara Road, highlighted in blue.

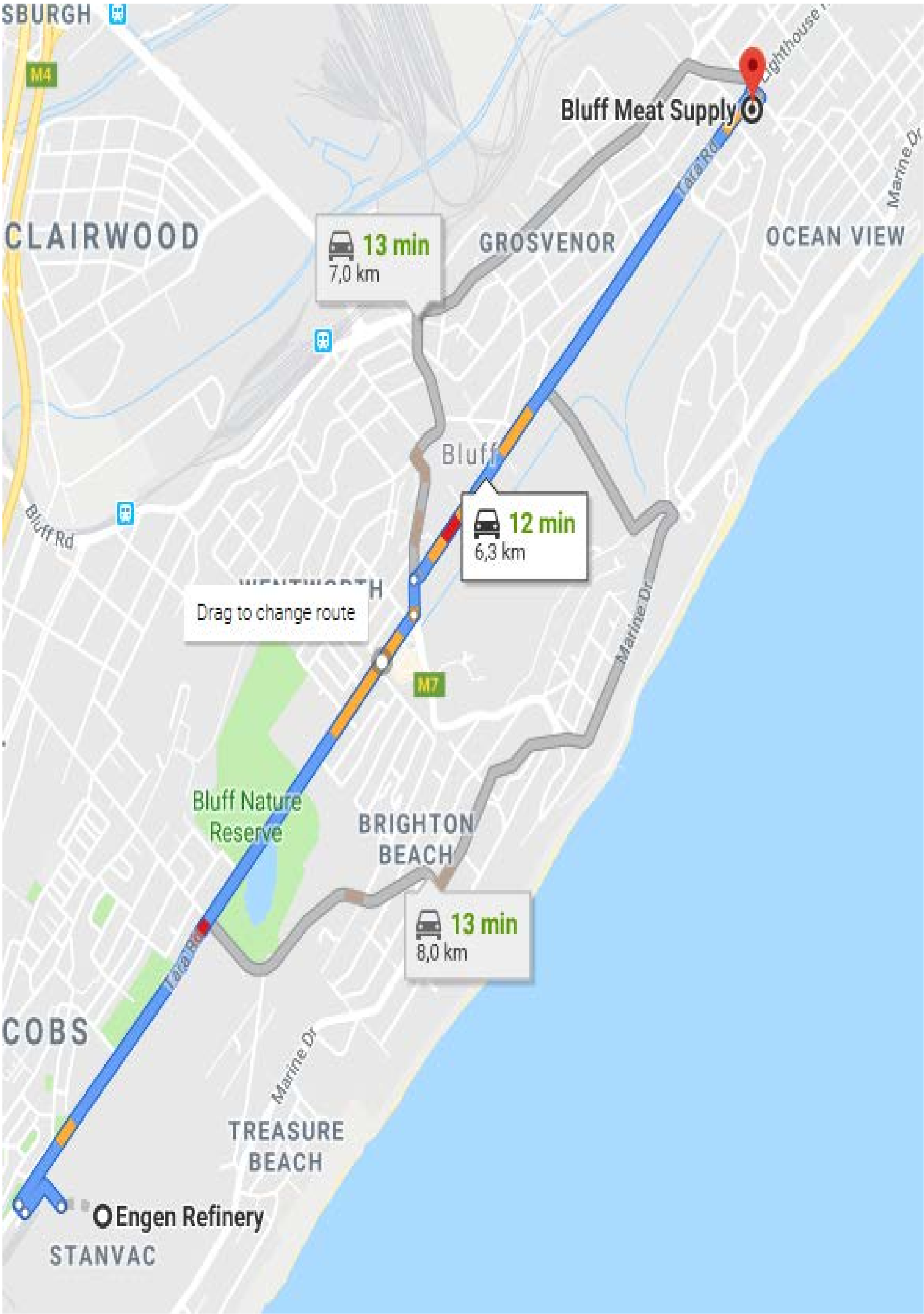


Figure 4.1: Research route on the Engen Petroleum Refinery transfer lines

Table 4.1: Pipe-to-soil ON spot potential results

Test post (TP)	Location	Pre-spot potential survey (V)	Post-spot potential survey (V)
TP10	Tara Rd, Across Quality Street	-2.621	-2.091
TP11	Tara Rd. north of TP 10	-1.866	-1.756
TP12	Tara Rd, at swamp	0.300V	No cable connection
TP13	Tara Rd	-1.492V	-1.501
TP14	Tara Rd	-1.436V	-1.345
TP15	Tara Rd, near Angelier Road	-1.344V	-1.529
TP16	Tara Rd, near Olsen Road, opposite checkers	-1.575V	-2.205
TP17	Tara Rd, opposite checkers	-1.775V	--2.028
TP18	Tara Rd	-0.904V	-1.082
TP19	Tara Rd	-1.142	-1.162
TP20	Tara Rd	-2.082	-1.980
TP21	Tara Rd	-1.755	-1.683
TP22	Tara Rd, Across Medical Centre TRU	-1.155	-1.507
TP23	Tara Rd near church	-1.410	-1.995
TP24	Island View Rd	-1.138	-0.873
TP25	Island View Rd	-2.06	-1.035
TP26	Island View/ Venezuela Rd	-1.956	-1.422
TP29	Ivernia Rd	-2.116	-1.725
TP30	30, Ivernia Rd	-1.795	-1.763
TP31	31, Ivernia Rd	-2.116	-1.912
TP39	Fynnland Station (Train Station)	-1.795	-1.740
TP43	Tara Rd / Light house	-1.156	-1.241

4.2.1 Analysis of pipe-to-soil ON spot potential results

The low potential observed on the baseline survey results at TP12 indicates that the cables to the pipe may be disconnected. This low potential started after a new fence had been erected at the nature reserve. It is possible that the test post cables were damaged during the erection process. Test post 18 also indicates a low potential reading. Since the transformer rectifier unit at Checkers was set to maximum this could be an indication that the ground bed is depleted.

Another low potential on the post was observed as well on TP24. Furthermore, the two low potentials on TP18 and 24 need to be investigated but the majority of the transfer lines are adequately protected when utilising a minimum of 100 mV(CSE) polarisation criteria.

4.3 Dynamic stray current influence on pipe potential survey results

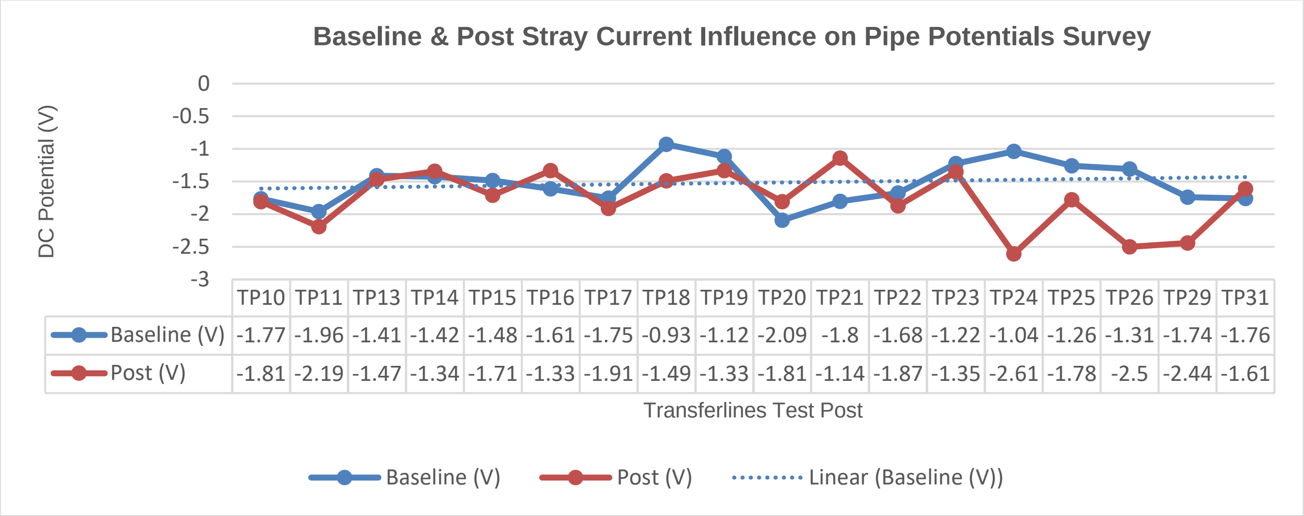
The stray current test implementation was to determine the source of the stray current, magnitude of stray current, at what areas the stray current enters the structure, at what areas the stray current leaves the structure and how the stray current can be mitigated. Dynamic stray currents were detected from the ON structure-to-electrolyte potentials. It was recorded in a 24-hour period. Dynamic stray currents can be indicated by a structure-to-electrolyte potential that is changing with time with the reference electrode in a stationary position in contact with the electrolyte.

Based on Miner et al, the -850 mV criterion with CP applied is the criterion most commonly used in areas of significant dynamic stray current activity. It is generally accepted that the structure is protected at a test location if the potential of the structure remains more negative than -850 mV(CSE) at all times, even with significant fluctuations associated with the dynamic stray currents [32].

In Larsen et al.'s findings, corrosion can only occur when the pipeline CP potential falls below -850 mV(CSE), while overprotection can happen when the threshold potential of the pipeline coating is overrun by the applied CP potential [2].

The greatest potential fluctuation magnitude (PFM) allowed for a buried steel pipeline, which is cathodic protected, depends on its coating material and is therefore determined via its safe potential range (SPR). For a steel pipeline with coal tar coating the maximum allowed potential before entering corrosion hazard zone is -850 mV(CSE), while the minimum allowed potential prior to overprotection is -2100 mV [2].

If the fluctuation magnitude in the subway traffic hour does not exceed 100mV, the dynamic stray current present will not be much of a concern if potential is safely within SPR[32]. The baseline and post survey recordings obtained for the transfer lines are presented graphically in Figure 4.2.



	TP10	TP11	TP13	TP14	TP15	TP16	TP17	TP18	TP19	TP20	TP21	TP22	TP23	TP24	TP25	TP26	TP29	TP31
Baseline (V)	-1.77	-1.96	-1.41	-1.42	-1.48	-1.61	-1.75	-0.93	-1.12	-2.09	-1.8	-1.68	-1.22	-1.04	-1.26	-1.31	-1.74	-1.76
Post (V)	-1.81	-2.19	-1.47	-1.34	-1.71	-1.33	-1.91	-1.49	-1.33	-1.81	-1.14	-1.87	-1.35	-2.61	-1.78	-2.5	-2.44	-1.61

Figure 4.2: Baseline and post survey spot potential results

4.3.1 Analysis of dynamic stray current influence on pipe potential results

Upon the inspection of these dynamic stray current results in Figure 4.2, it is clear that there is stray current present at all test posts. The most severe stray current was experienced at test posts (TP): 11, 20, 22, 24, 26, and 29. Most of these test posts are close to an electrified railway line, the most likely source of the excursions.

Test post 29 is at the Fynnland Train Station and thus provides a good entry point for the current into the pipe. However, on average the stray currents were not severe enough to push the pipe potential into the unprotected range. The amount of time that the pipe-to-soil potential was more negative than -0.9 V(CSE) gives an indication of the level of protection on the pipeline.

4.4 TRU output versus ground bed resistance results

This survey was performed to determine transformer rectifier unit efficiency and anode ground bed performance. The recordings for this survey are presented in Table 4.2 below.

Table 4.2: TRU output versus anode ground bed results

Item	Baseline survey			Post survey		
TRU location	**Output voltage (V)**	**Output current (A)**	**AGB resistance (Ω)**	**Output voltage (V)**	**Output current (A)**	**AGB resistance (Ω)**
Travancore Drive	34.5	7.80	4.42	9.19	10.37	0.89
Swamp	45.04	5.57	8.09	14.48	15.18	0.95
Checkers	62.69	13.55	4.63	30.3	25.44	1.19

4.4.1 Analysis of TRU output versus ground bed resistance results

According to Agarwal et al., the effective anode ground bed should have operating resistance below 2 Ω [27]. When analysing the baseline results, a conclusion was made that the anode ground beds in all the locations were reached at the end of their lifespan and they were due for replacement.

The analysis of the post survey results shows that an upgrade of anode ground beds in all the locations did improve the system performance in terms of CP current system demand, voltage and high efficiency anode ground bed. The overall cathodic protection system performance was improved based on the comparison of recorded results of the baseline and post survey data.

4.5 Soil resistivity survey results

This survey was performed with the aim to verify whether the soil resistivity around the location of all the anode ground beds does not have any impact on or contribution to the performance of the transformer rectifier unit and anode ground bed.

Soil resistivity is an indication of a given soil's ability to carry electric current. The flow of electricity in the soil is largely electrolytic, determined by the transport of ions dissolved in moisture. It is considered the most comprehensive indicator of a soil corrosivity. Typically, the lower the resistivity, the higher the corrosivity will be.

The main objective of measuring soil resistivity is for finding the best location and depth for low resistance. In this case, it was used as a good guide to provide an appropriate cathodic protection for Engen transfer lines.

The Direct Resistivity Soil (DRS) survey was conducted using the Dr. Frank Wenner method or 4-terminal method of measuring earth resistivity. In the DRS survey, the four-terminal instrument automatic soil resistivity tester (ABEM TERRAMETER, SAS1000/4000) was used to measure earth resistivity. The tester connection circuit diagram is the same as that in Figure 3.15. The following Wenner formula applies:

The centre point was picked and four instrument terminals were connected by leads to four metal probes driven into the soil with equal spacing. The horizontal spacing on the surface was determined by and equal to the depth to which the soil is to be measured. The tester was set, energised and readings were saved in the tester.

The resistivity values that were obtained represent the average resistivity of the soil to a depth equal to the pin spacing. The resistance measurements were typically performed to a depth equal to that of the pipelines being evaluated.

The results were downloaded from the tester to a PC for analysis. The resistivity results values were plotted using colour coding for easy interpretation. The recordings obtained around the vicinity of all the anode ground bed locations along the transfer lines are graphically presented in Figures 4.3 and 4.4. The dark blue colour is the lowest resistivity location, the blue colour is lower resistivity, dark green is low resistivity, green is medium resistivity, yellow is medium high resistivity and orange is the high resistivity location.

Figure 4.3 shows the results of the DRS survey conducted at the Swamp TRU area.

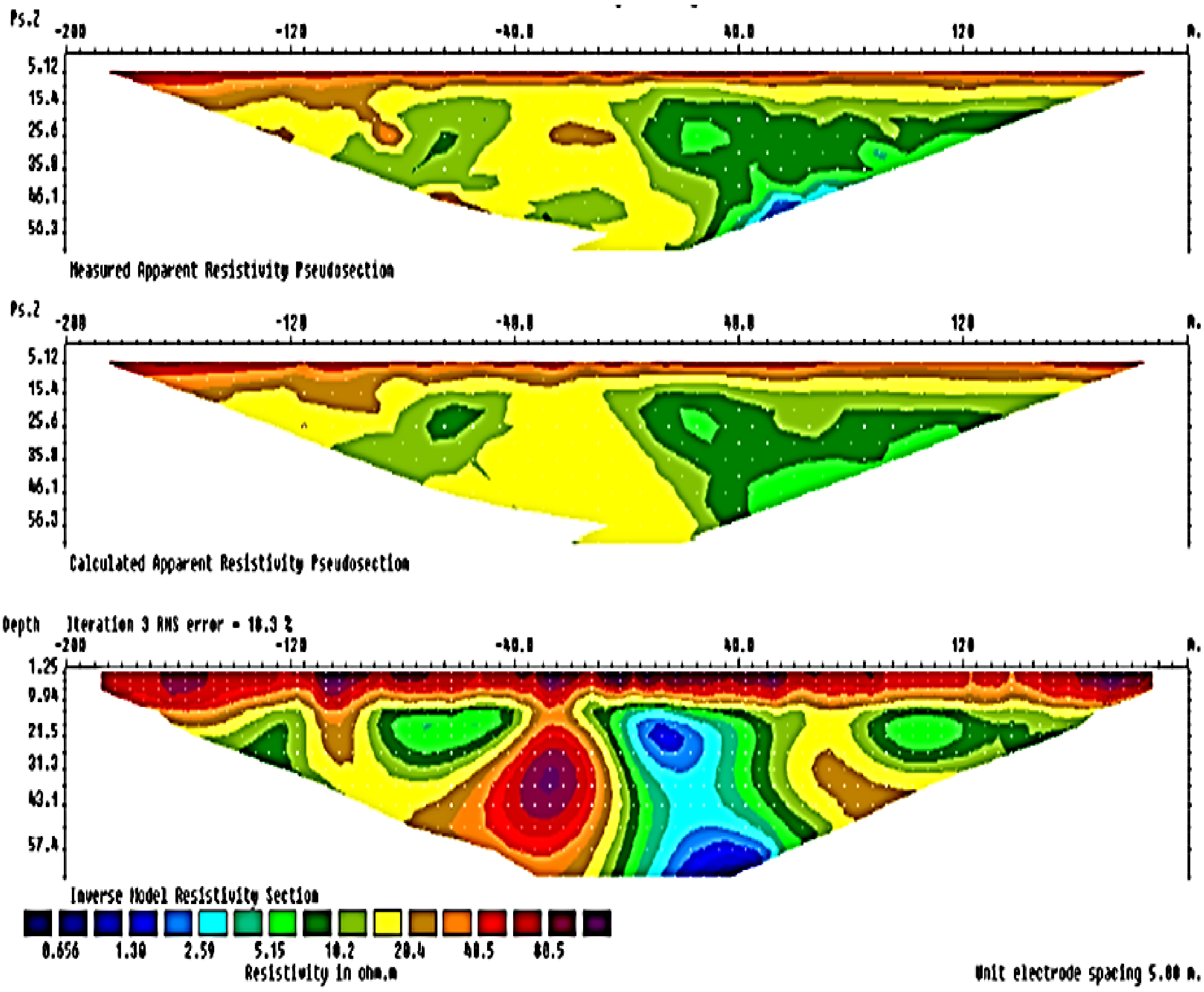


Figure 4.3: Swamp DRS soil resistivity results

Figure 4.4 illustrates the results of the soil resistivity survey conducted at the Checkers area using DRS equipment. The results show a definite area of low resistivity between -40 m and +40 m (metres).

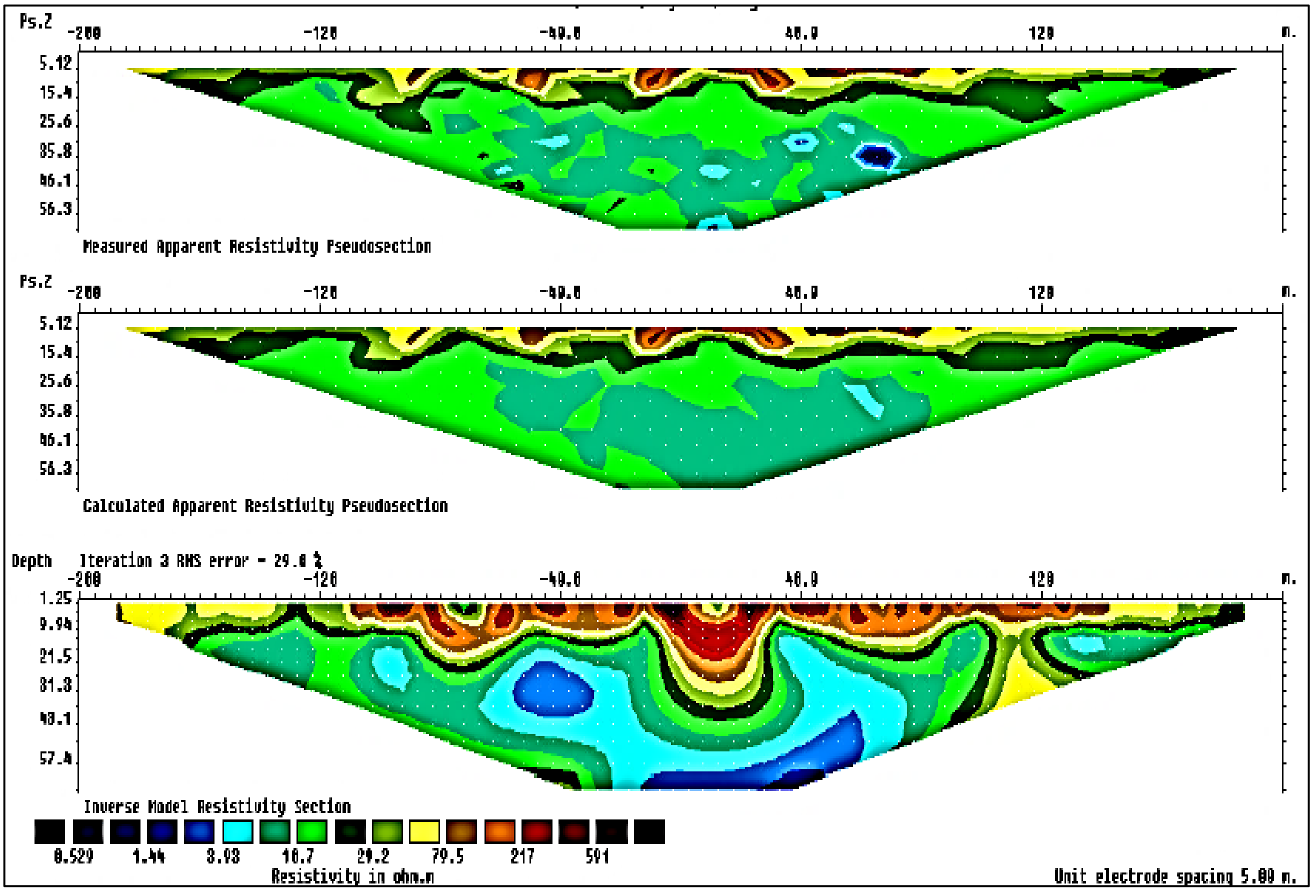


Figure 4.4: Checkers DRS soil resistivity results

4.5.1 Analysis of the soil resistivity survey results

Upon the analysis of the soil resistivity results, using Agarwal et al.'s research findings, it shows a definite area of low resistivity between 0 and +40 m on both areas at Swamp and Checkers. This is the vicinity where the anode ground bed was upgraded. This implies that, regarding the poor performance of the TRU and anode ground bed resistance during the baseline survey, soil resistivity did not contribute to the poor performance.

4.6 Insulation flanges test results

There are two sets of isolation flanges (IF) existing on the transfer lines as outlined:

- Isolation flanges on the north side of Engen Refinery, on Tara Road at the Engen Sports Complex near Highbury Road where the above ground pipeline enters the ground.
- At Venezuela Road Pipe Bridge on the South side of Island View B, as shown in Appendix B.

The isolating flanges on the transfer lines, both at the Engen Refinery and the Venezuela Road Pipe Bridge, were tested for efficacy. They were found to be functional.

This was performed to check the integrity of isolation flanges and cathodic protection current leaks.

Table 4.3 Integrity of insulation flanges at North side of Engen Refinery

Pipe size in (inch)	Live side (VDC)	Dead side (VDC)	Voltage across (VDC)	RF Status
14 inch	-2.334	-0.287	1.340	0k
6 inch	-2.531	-0.178	11.550	Ok
6 inch	-2.638	-0.009	1.547	Ok
8 inch	-2.541	-0.042	1.559	Ok
4 inch	-2.578	-0.101	1.524	Ok
4 inch	-2.525	-0.185	1.631	Ok
8 inch	-2.647	-0.198	1.872	Ok
10 inch	-2.464	-0.166	1.777	Ok

4.6.1 Analysis of insulation flange recordings

Based on the results in Table 4.3, the integrity of the insulation flanges is still complying and functioning accordingly. The recording on the dead side of the isolating flange is less than -0.850V and recording on the live side of the isolating flange is more than -0.850V.

4.7 Combined CIPS and DCVG survey results

Figure 4.5 is a graphical representation of the combined CIPS & DCVG baseline survey results. Low instant “ON” and “OFF” cathodic protection potentials are seen around test post 18 at point (A), as shown in Figure 4.5.

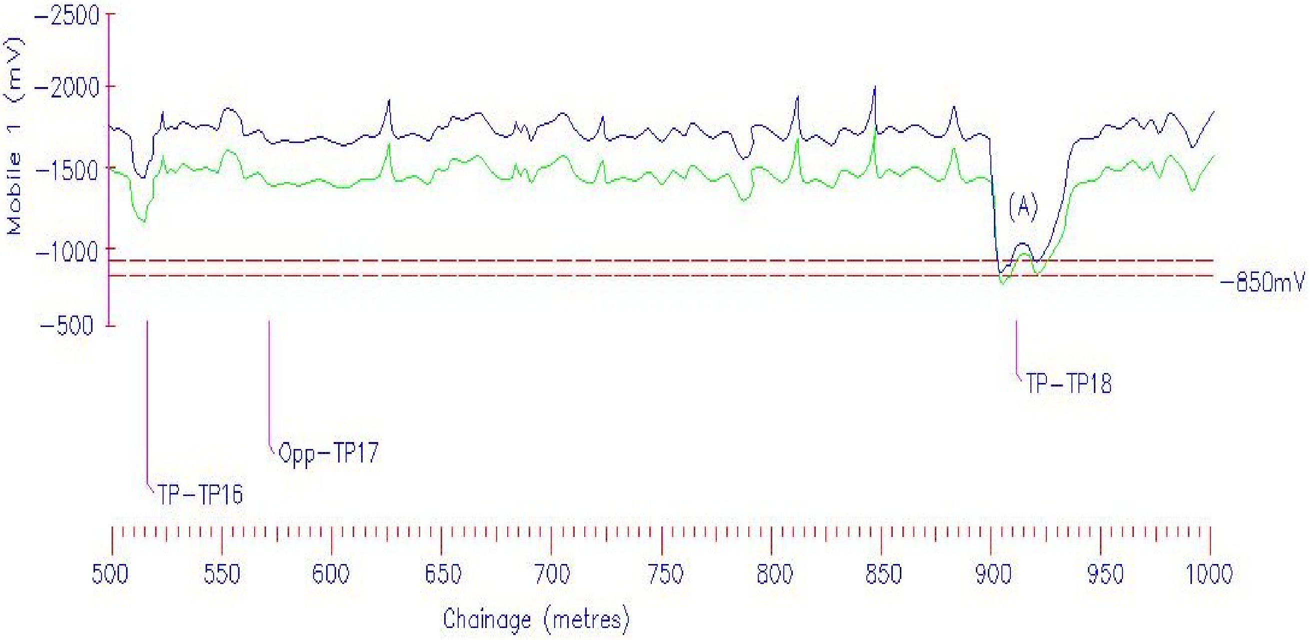
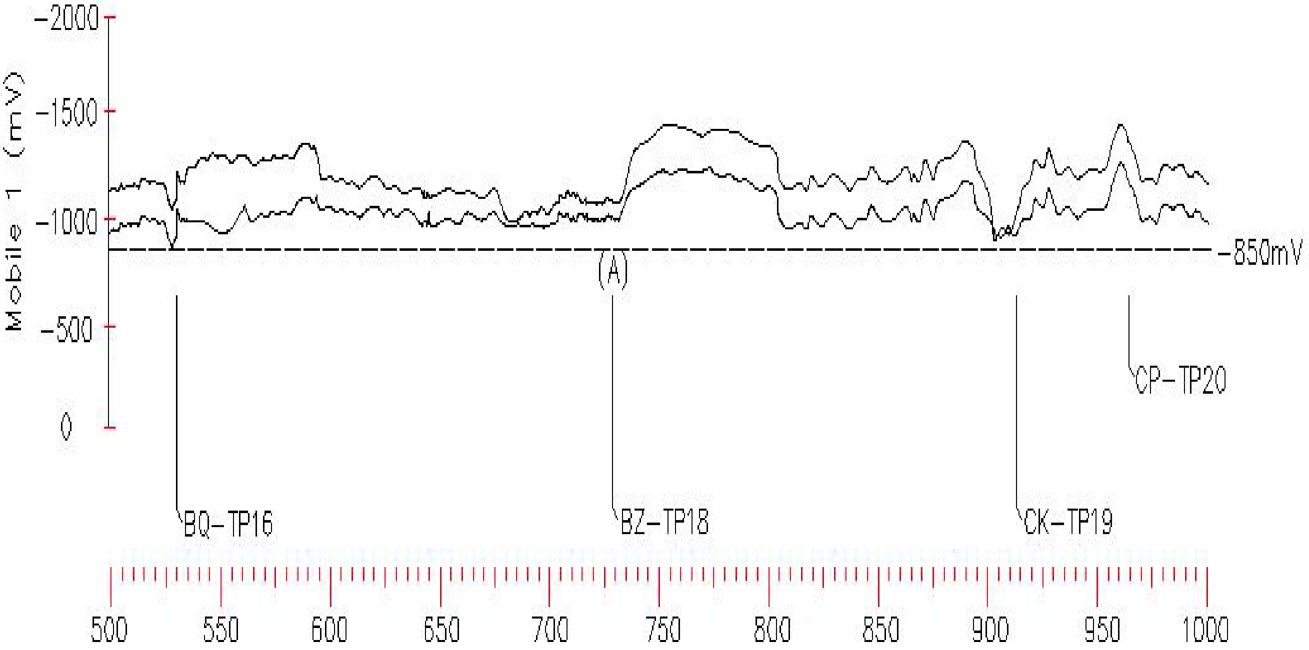


Figure 4.5: Combined CIPS and DCVG baseline survey results

Figure 4.6 is a graphical representation of combined CIPS & DCVG baseline survey results. There is an improvement of instant 'ON' and 'OFF' cathodic protection potentials around test post 18 at point (A), as shown in Figure 4.6.



Chainage (metres)

Figure 4.6: Combined CIPS and DCVG post survey results

4.7.1 Analysis of combined CIPS and DCVG survey results

The results are graphically presented in Figures 4.5 and 4.6. In referring to the NACE SP0169 standard, often a line is drawn across the graphed pages to easily identify the -850 mV (CSE) cathodic protection criteria, as shown on Figures 4.4 and 4.5.

A structure-to-electrolyte potential plot where the pipe meets the criteria will have all the structure-to-electrolyte potentials more negative than the line drawn at -850 mV (CSE), [2], as shown on Figures 4.5 and Figure 4.6 (see A). This criterion was selected based on the recommendations from the literature reviewed.

Figure 4.5 shows a baseline survey instant ‘ON’ and ‘OFF’ low cathodic protection less than -0.850V at test post 18. This indicates a possibility of a coating defect on this location. The post survey was performed six months later and results are shown in Figure 4.6. This survey was performed after maintenance and calibration had been done on the transformer rectifier units.

Analysis of the post survey results still indicate a low instant ‘ON’ and ‘OFF’ cathodic protection potential at test post, even though there is little improvement if compared to the baseline survey results of Figure 4.5. This confirms that there is a high possibility of a severe coating defect in this vicinity. When conducting this survey, 43 defects were located but the analysis is based only on the severe defects.

The pipeline is protected along the majority of the length. There still are signs of low cathodic protection potentials at test posts 18 and 25. Stray current was picked up between TP20 and TP29. This was also picked up during the post stray current influence survey and mitigation to control this stray current needs to be implemented in future. In conclusion, potentials along the pipelines indicate that the pipelines are, for the most part, adequately protected.

4.8 Field simulation survey results

4.8.1 ON and instant OFF pipe-to-soil potential survey results

The recordings obtained for the transfer lines’ ON and instant OFF spot potential survey are summarised in Table 4.4 – for all the test posts with coupons.

Table 4.4: Summary of instant OFF and ON spot potential recordings

Structure-to-soil potential (V)	**TP18 (V)**	**TP21 (V)**	**TP24 (V)**
ON spot potential	-1.692	-1.344	-1.244
Instant OFF spot potential	-0.944	-0.894	-0.985

4.8.2 Analysis of ON and instant OFF pipe-to-soil potential survey results

In referring to the NACE SP0169, a negative cathodic protection potential of at least 0.850 V (instant 'ON' and 'OFF) measured with cathodic applied with respect to the copper sulphate reference electrode contacting the electrolyte is required for adequate protection. Based on the analysis of the instant OFF potentials recordings, using -0.850 V NACE SP0169 instant OFF potential criteria in [2], indicates that the pipeline is adequately protected, even though borderline potentials were observed at TP21.

Chapter 5: Conclusion and Recommendation

5.1 Conclusion

The main aim of this investigation was to check the effectiveness of the impressed current cathodic protection on Engen transfer lines, current protection status, and mitigation action plan to resolve the findings. Baseline and post recordings for different types of recommended CP surveys, as mentioned in the literature review chapter, were executed.

The CP surveys were grouped into three categories, namely field observation, testing and simulation. An ON spot potential survey was performed on all test posts according to the NACE SP0169 100 mV polarization criteria on the entire transfer lines. The objective of this survey was to check whether the CP current has reached all the locations on the transfer lines.

CIPS and DCVG testing techniques were performed to determine if adequate cathodic protection is achieved at all points along the structure and for detecting cathodic protection current pickup at coating defects.

The CIPS and DCVG survey results have shown that the pipeline is protected. Improved protection is apparent in the vicinity of TP18 and 25 when comparing baseline and post survey results but still indicates low potential around these locations.

A supplementary field simulation CP technique using steel coupons was performed by measuring instant OFF potentials, using -850 mV_{CSE} NACE criteria. The results indicated that the pipelines are adequately protected in these vicinities, even though borderline potentials were observed at TP21. Stray current pickup was noted between TP20 and TP29. It was concluded that this is because these test posts are close to railway lines and mitigation on these locations is needed.

It was also noted during baseline testing of TRU output current and voltage that current is inversely proportional and anode resistance is out of the limit. A supplementary soil resistivity survey was performed on those locations. Good soil resistivity results were obtained. It was concluded, based on the analysis of results that the anode ground bed had reached its lifespan of 20 years.

After the replacement of the anode ground beds, a post survey was performed, which showed a huge improvement in terms of TRU, anode ground bed, pipe-to-soil potentials and system performance of the entire system transfer lines’ cathodic protection.

Analysis of the data collected during this investigation will contribute in setting up an effective monitoring system, identifying transfer line issues on time, and establishing a maintenance programme or plan to ensure the high efficiency of the Engen transfer lines system. Failing to maintain the transfer lines as per recommendations from Appendix B, may result in a major impact on the environment, people, plant equipment, organisation’s reputation, unplanned shutdown and might lead to the Trade Permit being taken by the state and shutdown of the plant.

5.2 Recommendation

Based on the knowledge gained from the literature review, field recordings and simulation findings about the status of Engen transfer lines in terms of cathodic protection, it is recommended that the organisation be proactive to prevent the catastrophic failure of the transfer lines that carry hazardous hydrocarbons. This should be done by sourcing a qualified, competent and reliable consultant company to perform frequent inspections and submit findings to the Engen team. Engen needs to draft a corrective action plan roadmap based on the findings.

There is need of a complete monitoring and maintenance programme that will have a detailed field survey over the entire cathodic protection system with brief inspections in between. The benefits of this programme will be that Engen can ensure that the conditions have not changed, and that output current and voltage are still adequate to meet the cathodic protection criteria. If at any stage it is found that this is not so, they need to make the necessary system parameter adjustments.

Internal resources or staff need to be trained to do recordings and analysis in order to support the organisation. This will contribute to maintenance cost savings, skills development, avoid unnecessary callout and to have reliable system. The recommended cathodic protection inspection intervals for regulated underground pipelines are as listed in Appendix B.

The analysis of the CIPS and DCVG results indicated that even though the AGB has been upgraded, there are still low potentials in locations around TP18 and TP21. It is recommended that, if possible, the organisation should excavate and do coating inspection on these locations and do rewrapping of the pipes.

During the field survey, it was noted that there is a gap in terms of getting enough information to make an effective decision for the system status. In this case, it would be a wise decision to install remote monitoring units in all TRU locations to monitor the system performance on a 24-hour basis. This will benefit the organisation in terms of system alarms and they will be able to respond quickly.

If they follow the above-mentioned recommendations, the organisation will be proactive and thus able to avoid unnecessary leaks and catastrophic incidents. They will have legal protection and will be complying with the trade permit. It will also be a wise decision to start rolling out a roadmap of feasibility studies to install CP systems on the tank farms for long-term benefits.

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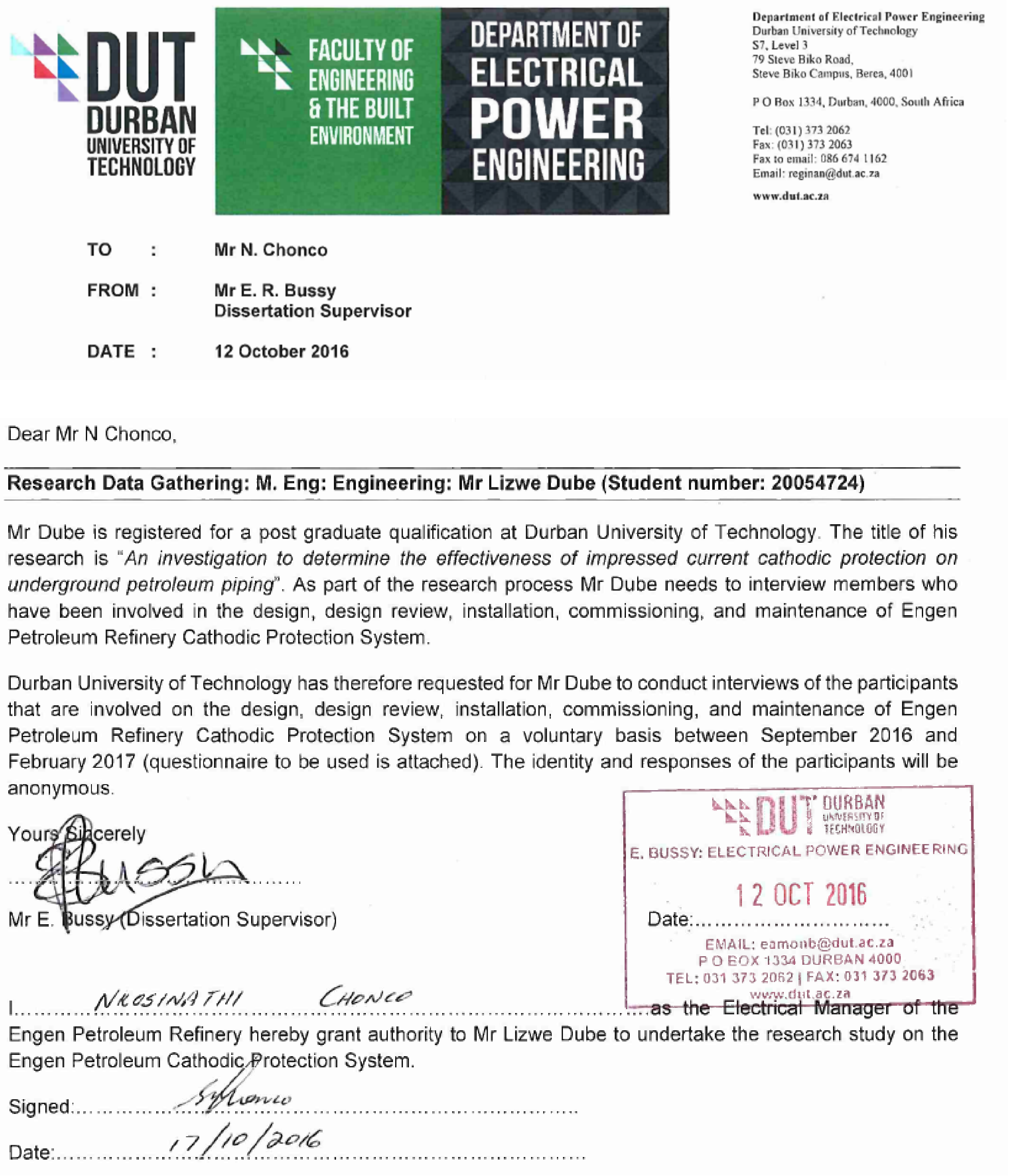
APPENDICES

Appendix A: Permit to conduct the study on Engen Petroleum Refine Cathodic Protection System



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TO : **Mr N. Chonco**

FROM : **Mr E. R. Bussy**
Dissertation Supervisor

DATE : **12 October 2016**

Dear Mr N Chonco,

Research Data Gathering: M. Eng: Engineering: Mr Lizwe Dube (Student number: 20054724)

Mr Dube is registered for a post graduate qualification at Durban University of Technology. The title of his research is "*An investigation to determine the effectiveness of impressed current cathodic protection on underground petroleum piping*". As part of the research process Mr Dube needs to interview members who have been involved in the design, design review, installation, commissioning, and maintenance of Engen Petroleum Refinery Cathodic Protection System.

Durban University of Technology has therefore requested for Mr Dube to conduct interviews of the participants that are involved on the design, design review, installation, commissioning, and maintenance of Engen Petroleum Refinery Cathodic Protection System on a voluntary basis between September 2016 and February 2017 (questionnaire to be used is attached). The identity and responses of the participants will be anonymous.

Yours Sincerely

……………………………………

Mr E. Bussy (Dissertation Supervisor)

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I……NKOSINATHI CHONCO……as the Electrical Manager of the Engen Petroleum Refinery hereby grant authority to Mr Lizwe Dube to undertake the research study on the Engen Petroleum Cathodic Protection System.

Signed:……………………………………

Date:……17/10/2016……………………

Appendix B: Cathodic Protection Intervals for Regulated Pipelines

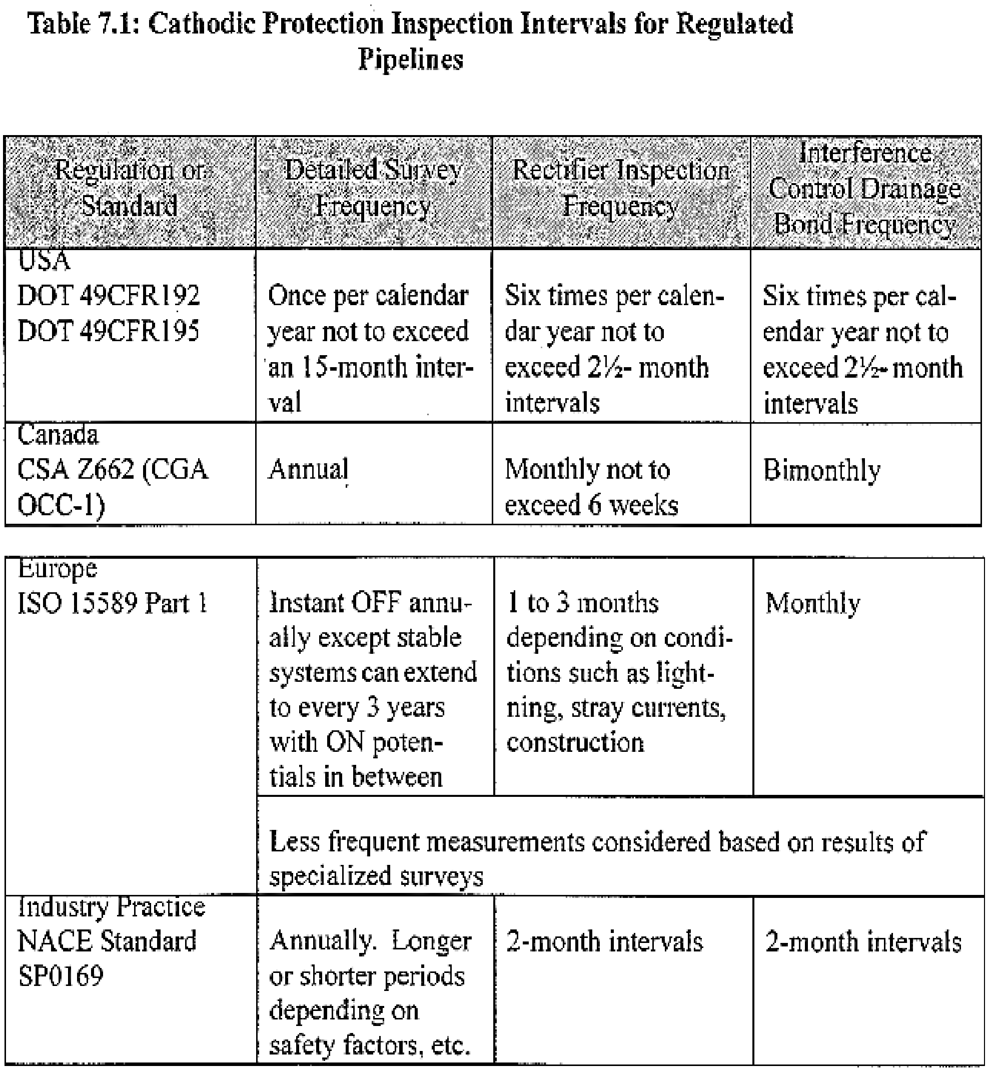


Table 7.1: Cathodic Protection Inspection Intervals for Regulated Pipelines

Regulation or Standard	Detailed Survey Frequency	Rectifier Inspection Frequency	Interference Control Drainage Bond Frequency
USA DOT 49CFR192 DOT 49CFR195	Once per calendar year not to exceed an 15-month interval	Six times per calendar year not to exceed 2½- month intervals	Six times per calendar year not to exceed 2½- month intervals
Canada CSA Z662 (CGA OCC-1)	Annual	Monthly not to exceed 6 weeks	Bimonthly
Europe ISO 15589 Part 1	Instant OFF annually except stable systems can extend to every 3 years with ON potentials in between	1 to 3 months depending on conditions such as lightning, stray currents, construction	Monthly
	Less frequent measurements considered based on results of specialized surveys		
Industry Practice NACE Standard SP0169	Annually. Longer or shorter periods depending on safety factors, etc.	2-month intervals	2-month intervals

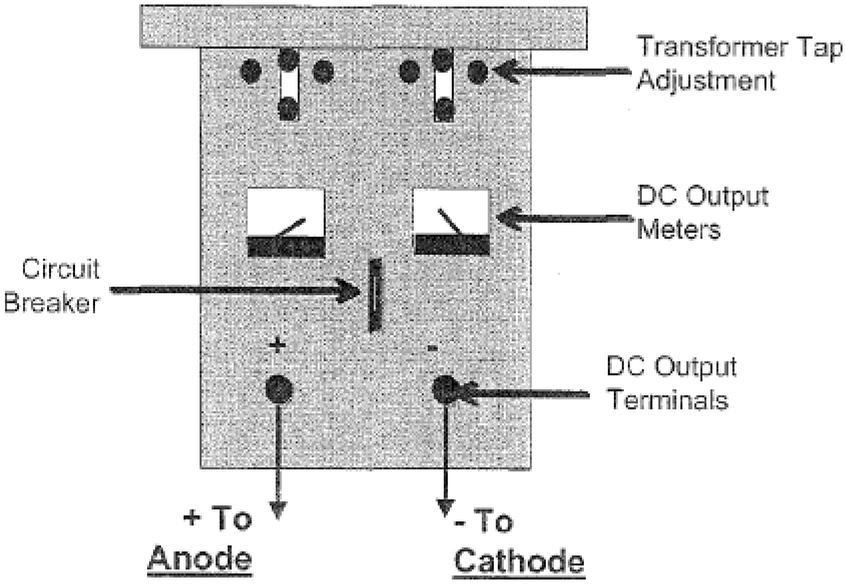
Table 7.1 Taken from NACE International Standard Practice- Measurement Techniques Related to Criteria for Cathodic Protection on Undergroung or Submerged Metallic Piping System

Appendix C: Engen transfer lines isolation flanges at Island View side

Picture taken by the Author showing isolation flanges on eight Engen Transferlines.

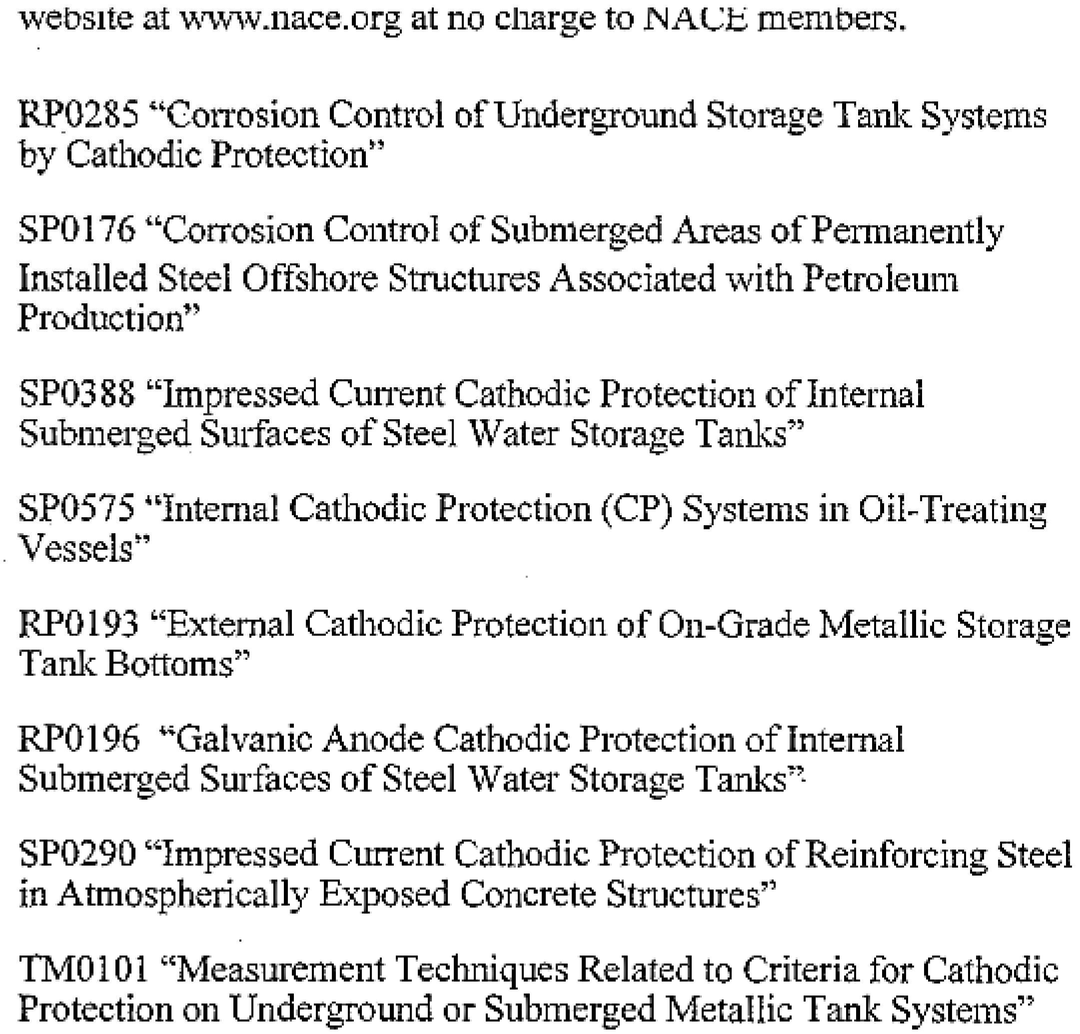
Isolation flange

Appendix D: A typical transformer rectifier unit control panel showing all the points where the TRU can be adjusted



Taken from NACE International SP0169-2007

Appendix E: Cathodic protection related NACE Standards



website at www.nace.org at no charge to NACE members.

RP0285 "Corrosion Control of Underground Storage Tank Systems by Cathodic Protection"

SP0176 "Corrosion Control of Submerged Areas of Permanently Installed Steel Offshore Structures Associated with Petroleum Production"

SP0388 "Impressed Current Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks"

SP0575 "Internal Cathodic Protection (CP) Systems in Oil-Treating Vessels"

RP0193 "External Cathodic Protection of On-Grade Metallic Storage Tank Bottoms"

RP0196 "Galvanic Anode Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks"

SP0290 "Impressed Current Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures"

TM0101 "Measurement Techniques Related to Criteria for Cathodic Protection on Underground or Submerged Metallic Tank Systems"

Taken from Romanoff, M., Underground Corrosion, NACE International Reprint, 1989.