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Topic

Study and realization of internal and external cathodic protection systems for fire-fighting water tanks

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ملخص

في إطار هاته المذكرة، هدفنا يرمي الى دراسة تطبيقية لأنظمة الحماية الكاثودية لثلاثة خزانات مائية موجهة لاستخدامات الأمان، المتمثلة في اخماد الحرائق في محطة كناندة غليزان، يعتبر هذا المشروع جزء من المشاريع الصناعية والحماية الكاثودية للهياكل المعدنية للشركة الوطنية للهندسة المدنية والعمارات.

في هذا العمل قمنا بدراسة نظرية وتطبيقية حول الحماية الكاثودية لخزانات الماء، بواسطة طريقة من أكثر الطرق استعمالا في هذا المجال والتي هي الحماية الكاثودية بالتيار المفروض من اجل حماية الاسطح الداخلية للخزانات من التآكل بسبب الماء بواسطة انودات سلكية، والسطح الخارجي السفلي من التآكل بسبب التربة بواسطة انودات شريطية.

كلمات مفتاحية

حماية كاثودية، تيار مفروض، خزانات ماء، كاثود، انودات شريطية، انودات سلكية.

Abstract

In this dissertation, we are aiming to study and realize cathodic protection systems for three fire-fighting tanks located in Kennanda Relizane. This project is part of the industrial and cathodic protection projects of the National Company of Civil Engineering and Buildings.

In this work, we have conducted a theoretical and practical study about the cathodic protection of water storage tanks, by one of the most commonly used methods in this field, which is impressed current cathodic protection.

We used wire anodes to protect the internal surfaces of the tanks from corrosion caused by water. And for the external bottom surfaces of the tanks, we used ribbon anodes to protect them from corrosion caused by the soil.

Keywords

Cathodic protection/ impressed current/ water storage tanks/ cathode/ ribbon anodes/ wire anodes.

Résumé

Dans ce mémoire, nous visons à étudier et réaliser des systèmes de protection cathodique pour trois réservoirs de l’anti incendies, situés à Kennanda Relizane. Ce projet s'inscrit dans le cadre des projets industriels et de protection cathodique de l'Entreprise Nationale de Génie Civil et Bâtiments.

Dans ce travail, nous avons effectué une étude théorique et pratique sur la protection cathodique des réservoirs de stockage d'eau, par l'une des méthodes les plus couramment utilisées dans ce domaine, à savoir la protection cathodique par courant imposé.

Nous avons utilisé des anodes en fil pour protéger les surfaces internes des réservoirs contre la corrosion causée par l'eau. Et pour les surfaces externes du fond des réservoirs, nous avons utilisé des anodes en ruban pour les protéger de la corrosion causée par le sol.

Mots clés

Protection cathodique/ courant imposé/ les réservoirs d’eau/ cathode/ anodes ruban/ anodes en fil

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Dedication

First of all, all praise and thanks are given to Allah, the most powerful and most merciful, who gave me the ability and patience to accomplish this work.

This project is dedicated to my dear mother, who was the most supportive person in my life and has always been by my side.

To my dear father, my source of inspiration, guidance, and strength.

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Nomenclature

Symbol	Signification	Unit
$\boldsymbol{S}$	Surface to be protected	m^2
$\boldsymbol{A}$	Surface of the anode	m
$\boldsymbol{D}$	Diameter of the tank	m
$\boldsymbol{r}$	Radius of the tank	m
$\boldsymbol{H}$	Wetted height of the tank	m
$\boldsymbol{V}$	Voltage	V
$\boldsymbol{U_m}$	Minimal voltage of the circuit	V
$\boldsymbol{U_r}$	Potential at a given distance	V
$\boldsymbol{I}$	Current requirement	A
$\boldsymbol{i}$	Current density	A/m^2
$\boldsymbol{i_0}$	Current density at 30℃	A/m^2
$\boldsymbol{I_s}$	Current output of the anodes MM	A/m
$\boldsymbol{I_m}$	Minimal current of protection	A
$\boldsymbol{N}$	Number of anodes	/
$\boldsymbol{W}$	Total number of distribution bar	/
$\boldsymbol{N_{16}}$	Total number of 16 mm^2 cable	/
$\boldsymbol{N_{35}}$	Total number of 35 mm^2 cable	/
$\boldsymbol{N_{50}}$	Total number of 50 mm^2 cables	/
$\boldsymbol{l}$	Width of ribbon anodes	m
$\boldsymbol{L_{min}}$	Minimal length of anodes	m
$\boldsymbol{T}$	Operating temperature	℃
$\boldsymbol{L}$	Spacing between the anodes m	m
$\boldsymbol{d}$	Depth of burial	m
$\boldsymbol{R}$	Bottom radius of the tank	m
$\boldsymbol{y_a}$	Length of ribbon anode in a single quadrant of the circle	m
$\boldsymbol{X_a}$	Spacing between anodes	m
$\boldsymbol{y_b}$	Length of distribution bars in a single circle quadrant	m
$\boldsymbol{X_b}$	Spacing between distribution bars	m
$\boldsymbol{r_a}$	Radius of the first series of string of anode wire	m
$\boldsymbol{d_a}$	Circumferential distance between the anodes	m

$\boldsymbol{d_s}$	Distance from the anode to the tank wall and bottom	m
$\boldsymbol{R_a}$	Average anode resistance	Ω
$\boldsymbol{R_T}$	Total resistance of the ribbon anodes	Ω
$\boldsymbol{R_{int}}$	Internal resistance of the anodes	Ω
$\boldsymbol{R_{ext}}$	External resistance of the anode	Ω
$\boldsymbol{\beta}$	Ribbon anodes resistance	$\Omega.m$
$\boldsymbol{R_{cn}}$	Average distribution bars resistance	Ω
$\boldsymbol{R_C^1}$	Linear resistance of the distribution bar	$\Omega.m$
$\boldsymbol{R_{TTi}}$	Total resistance of distribution bares	Ω
$\boldsymbol{R_{cables}}$	Total resistance of the cables	Ω
$\boldsymbol{R_{16}}$	Linear resistance of the cables 16 mm^2	Ω
$\boldsymbol{R_{35}}$	Linear resistance of the cables 35 mm^2	Ω
$\boldsymbol{R_{50}}$	Linear resistance of the cables 50 mm^2	Ω
$\boldsymbol{R_{cables}}$	Total resistance of the cables	Ω
$\boldsymbol{R_{Circuit}}$	Total resistance of the circuit	Ω
$\boldsymbol{R_{55℃}}$	Resistance of the anode wire at the temperature 55℃	Ω
$\boldsymbol{R_{18℃}}$	Resistance of anode wire at the temperature18℃.	Ω
$\boldsymbol{R_e}$	Resistance of the anode material	Ω
$\boldsymbol{L_m}$	Average length of an anode	m
$\boldsymbol{L_{mTi}}$	Average length of the distribution bar	m
$\boldsymbol{L_D}$	Length of the anode between two distribution bars	m
$\boldsymbol{L_{16}}$	Length of one 16 mm^2 cable	m
$\boldsymbol{L_{35}}$	Length of one 35 mm^2 cable	m
$\boldsymbol{L_{50}}$	Length of one 50 mm^2 cable	m
$\boldsymbol{EMF}$	Electro-motive force	V
$\boldsymbol{t}$	Lifespan	$years$
$\boldsymbol{\rho}$	Soil resistivity ($\boldsymbol{\Omega.m}$)	$\Omega.m$
$\boldsymbol{C}$	Water resistivity	$\Omega.m$
$\boldsymbol{f_{deterioration}}$	Deterioration factor of the internal surface coating	%
$\boldsymbol{f_c}$	Number of anodes correction factor	%
ENGCB	**E**ntreprise **N**ationale **G**énie **C**ivile et **B**âtiments	
SONATRACH	**S**ociété **N**ationale pour la **R**echerche, la production, le **T**ransport, la transformation, et la **C**ommercialisation des **H**ydrocarbures	
NACE	**N**ational **A**ssociation of **C**orrosion **E**ngineers	
GNP	**G**ross **N**ational **P**roduct	

Ph	**P**otential **H**ydrogen
CP	**C**athodic **P**rotection
Mic	**M**icrobiological **I**nfluenced **C**orrosion
DC	**D**irect **C**urrent
AC	**A**lternating **C**urrent
ONAN	**O**il Natural **A**ir **N**atural
T/R	**T**ransformer **R**ectifier
NJB	**N**egative Junction **B**ox
PJB	**P**ositive **J**unction **B**ox
TB	**T**est **B**ox
PEHD	**P**oly-**E**thylene **H**igh-**D**ensity
PCR	**P**olarizing **C**ell **R**eplacement
MMO	Metal Mixed Oxide
ENH	**E**lectrode **N**atural **H**ydrogen
PVDF	**P**oly-**V**inyli-**D**ene **F**luoride
HMWPE	**H**igh **M**olecular **W**eight **P**oly-**E**thylene
SPD	**S**urge **P**rotection **D**evices
DFT	**D**ry **F**ilm **T**hickness

General introduction

General introduction

Metals have been utilized by humans for thousands of years due to their unique properties and wide range of applications, and they became extremely popular in the late centuries because of the industrial revolution.

During the manufacturing and transformation of the minerals into metals, they gain and store internal energy that could be released in the appropriate conditions so the metals can go back to their natural form, which eventually leads to corrosion.

Corrosion is a natural process that occurs when certain materials, such as metals, come into contact with their environment. It is the gradual deterioration and disintegration of a material due to chemical or electrochemical reactions with substances in the surrounding environment. This phenomenon is a huge problem, especially in the industrial field, so anti-corrosion methods should be used to protect metallic structures and avoid costly repairs, like inhibition, coating, corrosion control by design, and cathodic protection.

Cathodic protection is a technique used to prevent or mitigate the corrosion of metal structures by making them the cathode of an electrochemical cell. By applying a direct electrical current, cathodic protection systems can protect metal surfaces from corrosion and extend their service life. There are two types of cathodic protection systems: the sacrificial anodes system and the impressed current system.

This project aims to design and explain the procedure for the realization of two cathodic protection systems for each of the three fire-fighting tanks located in the Kennanda–Relizane compression center. To provide adequate protection and extend the lifespan of the tanks.

This dissertation is divided into 4 chapters, as follows:

The first chapter is a presentation of the company responsible for the realization of this project.

The second chapter is an overview and explanation of the phenomenon of corrosion and its reactions.

The third chapter is an explanation of the different methods of controlling and minimizing the effects of corrosion, like coating, inhibition, corrosion control by design, and finally cathodic protection.

The fourth chapter explains the design procedure for two cathodic protection systems for each tank, one for the external bottom surfaces of the tanks, and the other for the internal surfaces of the tanks.

Chapter I

Presentation of the company ENGCB

I.1 Introduction

In this chapter, we have presented the company ENGCB, which is responsible for the study and realization of the fire-fighting tanks project, and it’s where we conducted our research in the cathodic protection department to give coherence to our study.

I.2 Presentation of the company

The national company of civil engineering and building, with the abbreviation ENGCB, is a company issued by the restructuration of SONATRACH, created on August 1, 1981, by presidential decree n° 81-173.

It was erected as a joint stock company in July 1998 with a share capital of 7630 million Algerian dinars.

I.3 Organization of the company

The company is organized into polyvalent regional structures, each of which has the material and managerial capacity to respond to the needs of ENGCB’s customers in its region. These regional structures have the support structures in transportation equipment, general, financial, and technical, as required by playing a regulatory role to optimize the means of the company.

GCB has a direction of engineering, architecture, and topography and a direction of metal structures production. With a known experience of more than 35 years in the different specialties of building, GCB fulfills the specifications of the most demanding customers.

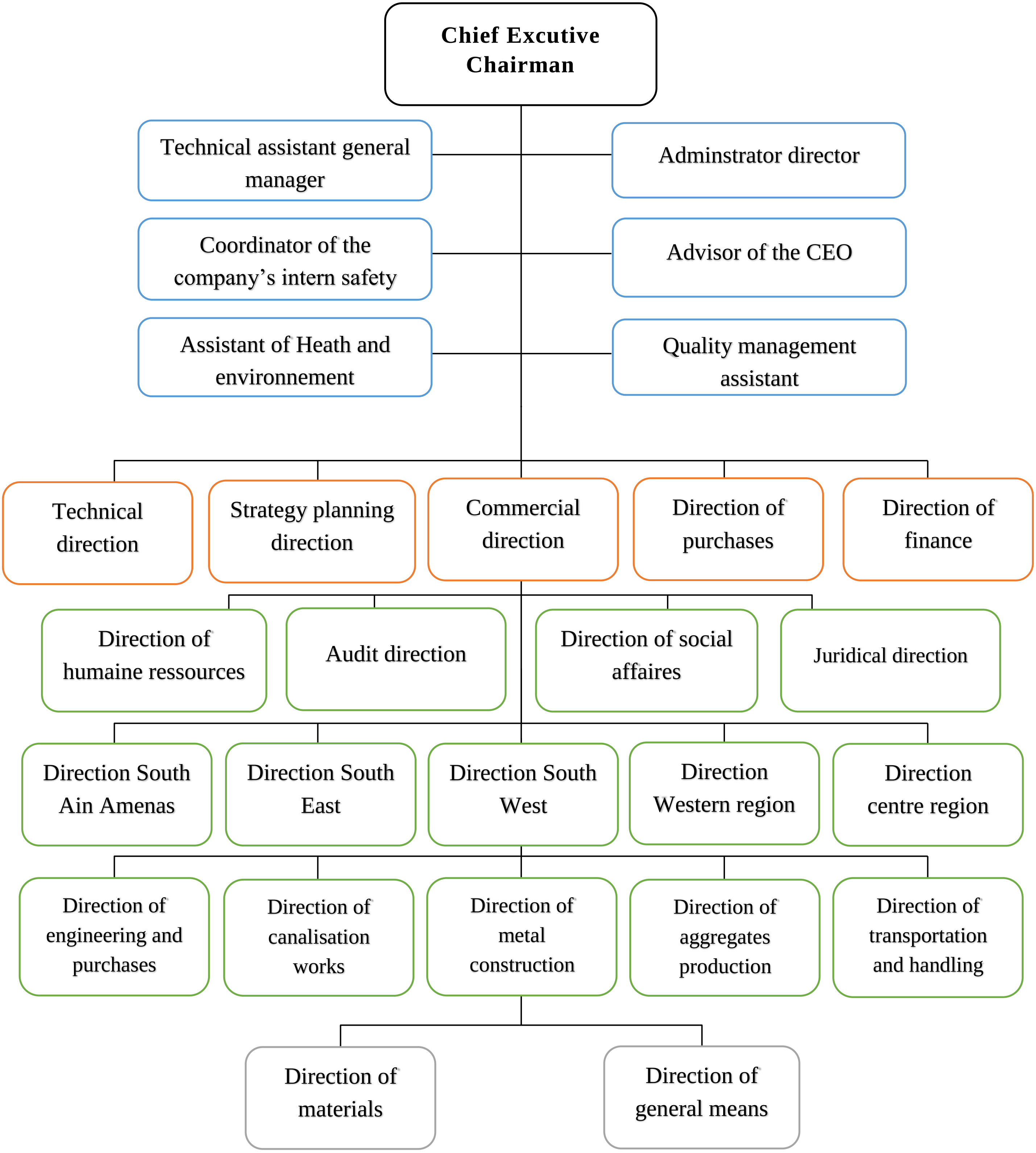

Figure I. 1 Flow chart of the company ENGCB.

I.4 The company's areas of work

- Engineering and procurement.
- Mass earthworks.
- Drilling platforms and access tracks.
- Industrial civil engineering of major oil and gas installations.
- Canalization works.
- Roads and highways achievement.
- Aerodromes and trail of landing achievement.
- Hydraulic constructions and transfer.
- Building and roads and utilities.
- Railway civil engineering.
- Metallic frames construction and boiler making.

Figure I. 2 Fields of work of ENGCB.

I.5 Resources

I.5.1 Human ressources

ENGCB spends an average of 40 million dinars on training and the improvement of its personnel, especially in the various company core businesses. Training is provided annually for about 1,000 employees in various technical and support fields, representing 7% of the total workforce.

Table I. 1 Total workforce of the company ENGCB.

ENGCB total workforce	15,300	100%
Managers	1,431	9%
Control	4,274	28%
Execution	9,595	63%

I.5.2 Material resources

ENGCB has a consequential park with more than 4.400 pieces of equipment, including 2800 engines and heavy equipment that is constantly upgraded, which gives the company an important autonomy of action.

I.5.3 Infrastructures

ENGCB has fixed infrastructures for industrial, administrative, and socio-professional use, especially implanted in:

- Algiers (kaidi bab-zouar).
- Algiers (industrial areas of El-Harrach, and Oued-Smar).
- Boumerdès (Boumerdès and Boudouaou).
- Arzew (industrial area of Arzew).
- Hassi-Messaoud – RhourdNouss – Nezla.
- Hassi-R’mel- Insalah –Adrar.
- In-Amenas –Illizi – Tin Fouyé Tabenkort.

ENGCB has the infrastructure and a life basis in its different building sites, with a capacity for the reception of more than 6,500 agents in the different project sites. (Studios, accommodation cabins, chalets, canteens, etc.).

Chapter II

Basic concepts of corrosion

II.1 Introduction

Humans have struggled a lot with the problem of corrosion throughout history. It has serious economic, environmental, and safety consequences by damaging infrastructure, and leading to costly repairs.

In this chapter, we take an overview of what corrosion is, its reactions, the different cells of corrosion, the cost of it, and also the factors that influence its rate.

II.2 Definition of corrosion

NACE International defines corrosion as the deterioration of a material, usually metals, resulted from a reaction with its environment **[1].**

We can also define corrosion as an electrochemical process involving the flow of electrons and ions with oxidation and reduction reactions, which eventually lead to the weakening or perhaps the failure of the material.

II.3 Anodic and cathodic reactions

II.3.1 Anodic reaction

The process of oxidation in most metals and alloys represents corrosion, which is the release of electrons and cations. Hence, if oxidation is stopped, corrosion is stopped **[2].**

$A \rightleftharpoons A^{n+} + ne^-$ **(II. 1)**

II.3.2 Cathodic reaction

Cathodic reactions are reduction reactions, which involve the gaining of electrons which are realesed at the anode **[2].**

Two of the most common reduction reactions that occur at the surface of the cathode are:

- Oxygen reduction, more common in neutral environments:

$2H_2O + O_2 + 4e^- \rightleftharpoons 4OH^-$ **(II. 2)**

- Hydrogen ion reduction, more common in acidic environments:

$H^+ + e^- \rightleftharpoons H$ **(II. 3)**

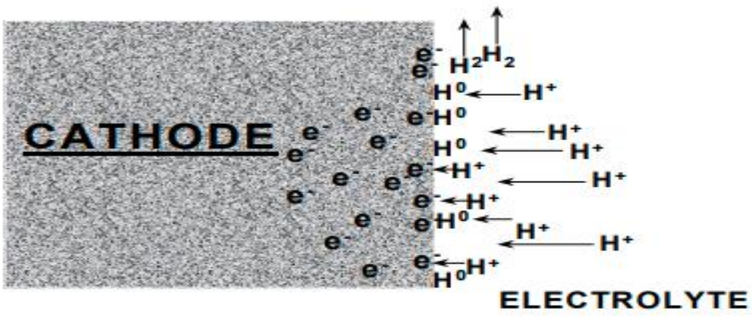

Figure II. 1 Reduction reaction happening at the surface of the cathode **[1].**

II.4 Corrosion cells

II.4.1 Definition

For corrosion to take place, the formation of a corrosion cell is essential. A corrosion cell is essentially comprised of the following four components: anode, cathode, electrolyte, and a metallic path **[1].**

II.4.2 Types

II.4.2.1 Galvanic cells

The galvanic cell may have an anode or cathode of dissimilar metals in an electrolyte or the same metal in dissimilar conditions in a common electrolyte **[2].**

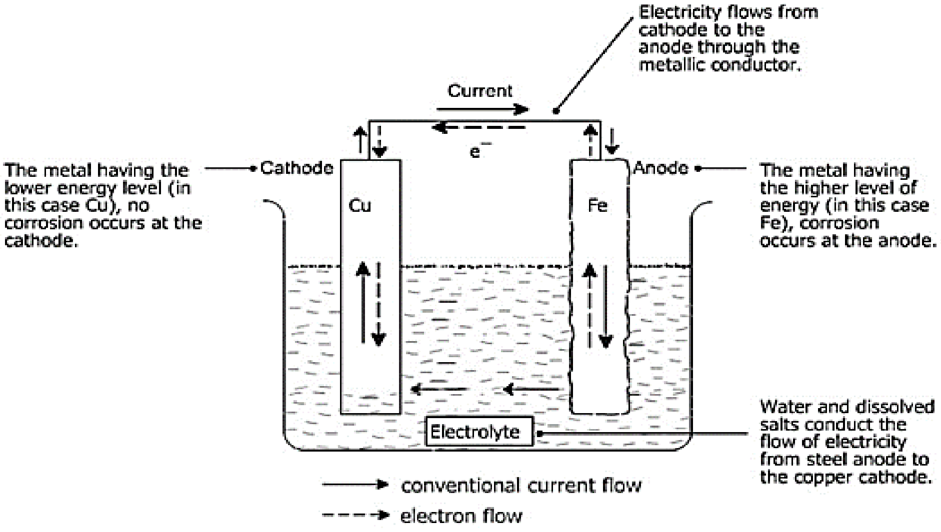

Figure II. 2 Galvanic cell **[2].**

II.4.2.2 Concentration cells

This is similar to galvanic cells except with an anode and cathode of the same metal in a heterogeneous electrolyte. For example, the corrosion of a pipe in the soil **[2].**

II.4.2.3 Electrolytic Cell

This type of cell is formed when an external current is introduced into the system. It may consist of all the basic components of galvanic cells and concentration cells plus an external source of electrical energy **[2].**

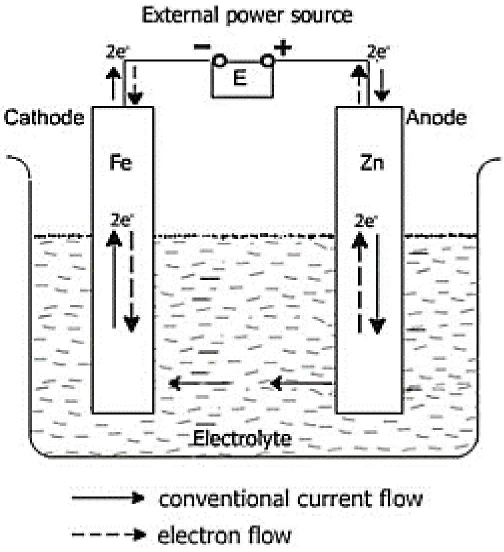

Figure II. 3 Electrolytic cell **[2].**

II.4.2.4 Different temperature cells

This type of cell is formed when two electrodes of the same metals are present in different temperatures, causing in different potentials **[2].**

II.5 Types of corrosion

II.5.1 Uniform corrosion

It is the thinning of the metal without any localized attack, it doesn't penetrate deeply, for example, the rusting of steel in the air **[2].**

II.5.2 Galvanic corrosion

When two different metals are electrically linked and submerged in a conductive solution, galvanic corrosion happens. The anode is corroded, while the cathode is protected **[2].**

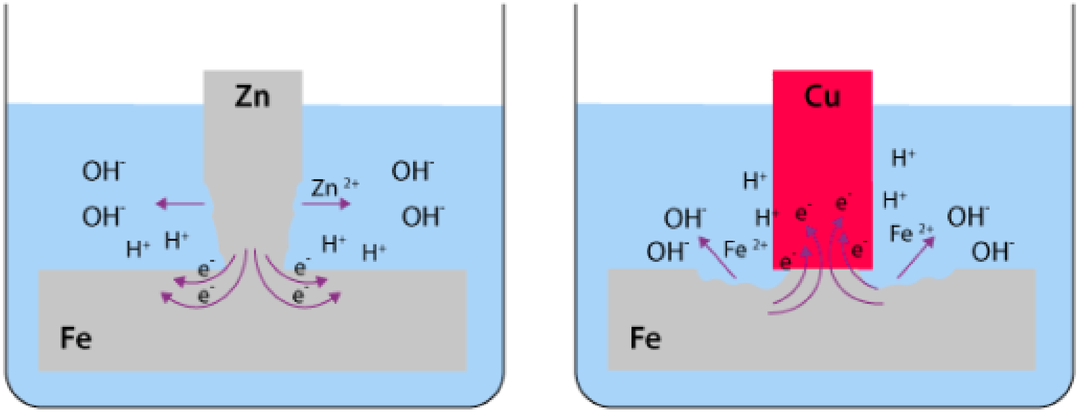

Figure II. 4 Galvanic corrosion mechanism.

II.5.3 Pitting corrosion

Pitting corrosion is a specific type of corrosion that causes holes or cavities to develop in the material. Pitting is considered more dangerous than uniform corrosion damage because it is more challenging to detect, anticipate, and design against **[2].**

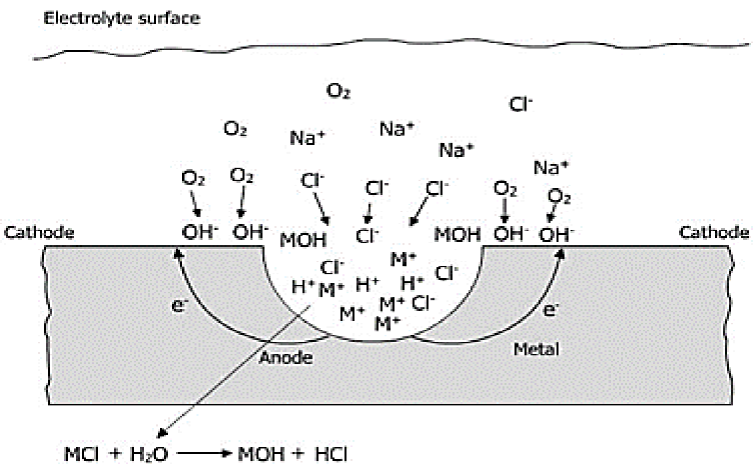

Figure II. 5 An active corrosion pit on a metal **[2].**

II.5.4 Selective corrosion

Also called "dealloying" it involves the selective dissolution of one of the elements in a single-phase alloy or one of the phases in a multiphase alloy. The most well-known example is the dezincification of brass **[3].**

II.5.5 Erosion corrosion

Erosion Corrosion is the result of both corrosion and erosion and is brought on by the rapid flow of any turbulent fluid across a metal surface. Turbulence is primarily brought on by pitting, which is often found on the interior surfaces of pipelines **[3].**

II.5.6 Stress corrosion cracking

Stress corrosion cracking is a form of localized corrosion that produces cracks in metals through the simultaneous action of a corroding species and sustained tensile stress **[2].**

II.6 Factors that affect corrosion

II.6.1 The conductivity of the electrolyte

It is determined by the amount of ions in the electrolyte, more ions represent more current, thus an increase in corrosion rate **[4].**

II.6.2 Anode/Cathode Ratio

The anode of a corrosion cell corrodes at a rate that is significantly influenced by the relative area between the anode and cathode. If the anodic area is small in relation to that of the cathode, the anode will corrode rapidly. This is because the corrosion current is concentrated in a small area. Additionally, the large cathode might be difficult to polarize, maintaining a high rate of corrosion.

When a small cathode is connected to a large anode, the corrosion current density on the anode is much lower than in the opposite case discussed above, and the anode corrodes more slowly.

Polarization might be significant in this case as well. The small cathode may polarize rapidly, reducing the rate of corrosion current flow **[4].**

II.6.3 Moisture content

Electrolytic corrosion requires the presence of moisture. A completely dry environment will not support this form of corrosion.

In comparison to a surface that is completely submerged, a damp, well-aerated metal surface may experience faster general corrosion.

In underground corrosion, the high moisture content is generally associated with increased corrosion rates. Total submersion (saturated soil) is not always the most aggressive circumstance, though **[4].**

II.6.4 Chemical reactions of the electrolyte

It is the chemical activity of the electrolyte that provides the redox (oxidation-reduction) reactions necessary to drive a corrosion cell. Some of the chemical species present in an electrolyte may assist in retarding or slowing chemical action by aiding the production of protective films **[4].**

Also, a lower PH means a high concentration of H^+ ions, so in some cases, there are metals more active than hydrogen, like aluminum and magnesium, which will corrode, unlike more noble metals.

Amphoteric metals like aluminum and lead can experience accelerated corrosion in highly alkaline conditions, typically with a pH higher than 8.

II.7 Causes of corrosion

II.7.1 Natural reaction corrosion

II.7.1.1 Dissimilar metals

Refers to corrosion damage induced when two dissimilar materials are coupled in a corrosive electrolyte. And because of the difference in potential between these two materials, a direct current will be generated and flow from the more active material, called the anode, to the more noble metal, called the cathode. The galvanic series indicates which metals will become anodic or cathodic in a metallic couple **[1].**

II.7.1.2 Alloying

Alloys are metallic substances composed of two or more elements, in the alloying process, grain boundaries are formed. Similar to dissimilar metals, the grain boundary may be more active or more noble than the adjacent metal causing a voltage difference **[1].**

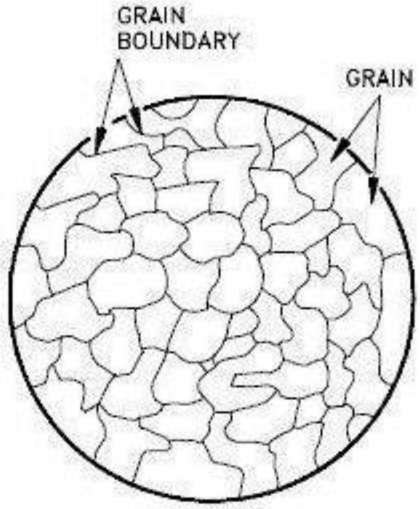

Figure II. 6 Microscopic view of alloys.

II.7.1.3 Mechanical Stresses

The area of a metal that is mechanically stressed the most is typically the area that is more active and serves as the anode of the corrosion cell **[1].**

II.7.1.4 Temperature Differences in the Metal

The area with the higher temperature is typically the more active area and serves as the anode of the corrosion cell when different sections of a structure are at different temperatures **[1,5].**

II.7.1.5 Oxygen Concentration

A metal exposed to various oxygen concentrations might experience a variation in voltage. Since oxygen is a cathodic reactant, the metal closest to the area of greater oxygen concentration will be more noble, hence the cathode **[5].**

II.7.1.6 Metal Ion Concentration

The higher the concentration of metal ions that are the same as the adjacent metal, the more noble the metal becomes. For metal ions that are different from the adjacent metal, the effect may be difficult to determine **[1].**

II.7.1.7 Dissimilar Soils

Due to their differences in conductivity (reciprocal of resistivity) and oxygen concentration, soils like clay and sand may accelerate corrosion. The anode is typically more active and located close to the soil with reduced resistivity **[1].**

II.7.1.8 Microbiological Influences

Microbiologically influenced corrosion (MIC), also known as microbiological corrosion or bio corrosion, is a type of corrosion caused by the metabolic activities of microorganisms such as bacteria, fungi, and algae. These microorganisms colonize the metal surface and produce corrosive byproducts such as organic acids, hydrogen sulfide, and ammonia, which react with the metal and cause corrosion **[1,5].**

II.7.2 Unnatural reaction corrosion

II.7.2.1 Definition

Unnatural reaction corrosion is stray current, which in cathodic protection refers to the unintended flow of electric current in a metallic structure that is being protected by cathodic protection. It can be alternating current which represents a safety hazard, or it can be a direct current that can cause corrosion **[1,3,5].**

II.7.2.2 Types of stray current

- **Dynamic current**

It refers to a fluctuating current that varies in amplitude and frequency. Dynamic current could be generated by:

- Transit systems.
- Mining.
- Electric power transmission.
- Telluric current.
- Industrial plants.
- DC welding machine

- **Static interference**

Static, or steady state, interference currents are defined as those that maintain constant amplitude and constant geographical paths. Examples include High-Voltage Direct Current, ground electrodes and cathodic protection systems **[3,5].**

And there are two types of static interference:

- **Anodic interference**

When the foreign structure has less potential than the protected structure, electrons will discharge to the foreign structure.

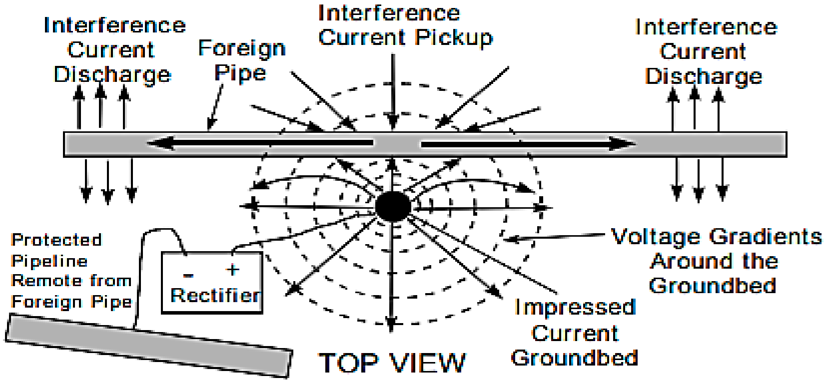

Figure II. 7 Mechanism of anodic stray current interference **[3].**

- **Cathodic interference**

When the foreign structure is more active than the protected structure, electrons will flow into the protected structure.

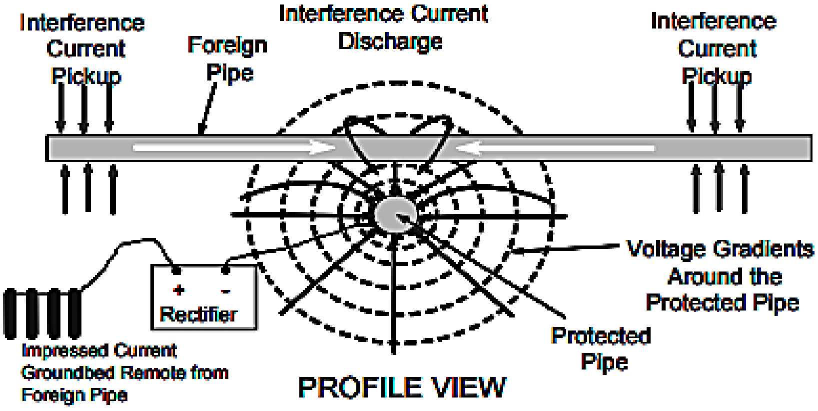

Figure II. 8 Mechanism of cathodic stray current interference **[3].**

II.7.2.3 Stray current control

We can resolve stray current interference problem by:

- Reposition anodes.
- Apply cathodic protection and coating to the impacted structure at the discharge location of the interfering current.
- Adjust the interfering system’s current output.
- Install mitigation bonds provide a metallic path between the affected structure and the source of stray current. This permits the current to be drained through the cable back to the source rather than leaving the structure through an earth path.

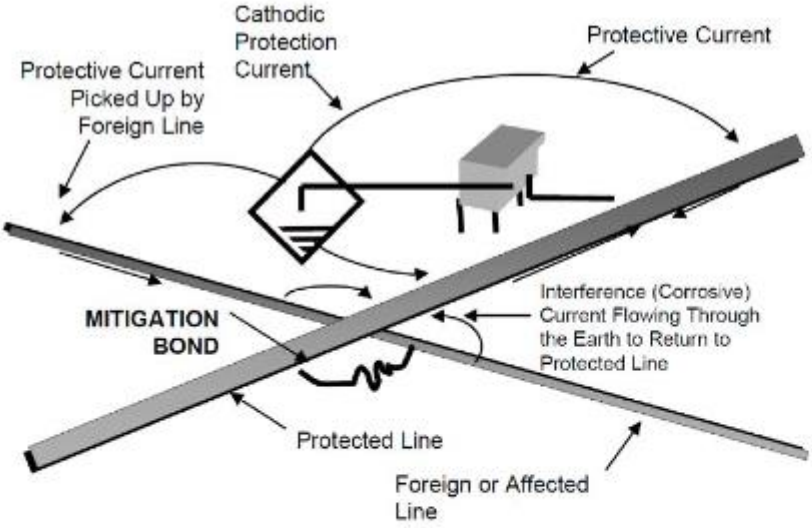

Figure II. 9 Mitigation Bond Used to Solve a Cathodic Interference Problem **[3].**

II.8 Cost of corrosion

In our today's society, corrosion is recognized as one of the most severe issues in the industrial field, with annual losses in the hundreds of billions of dollars. Numerous nations, including the United States, the United Kingdom, Japan, Australia, Kuwait, Germany, Finland, Sweden, India, and China, have conducted corrosion cost studies. The studies have included both official and thorough efforts as well as informal and small efforts. These studies all came to the same conclusion: the annual corrosion expenses for each country ranged from 3.5 to 5 percent of its Gross National Product (GNP) **[4].**

II.9 Conclusion

Corrosion can manifest in different forms, each with its own characteristics, appearance, and it can have significant economic and safety implications. It can weaken structures, reduce the lifespan of equipment, and cause failures in various industries, so understanding the mechanisms and types of corrosion is essential for developing effective strategies to mitigate and manage its impact and at least minimize its consequences.

Chapter III

Corrosion control methods

III.1 Introduction

The damages caused by corrosion forced humans to invent and come up with methods and special materials to control and monitor corrosion, these methods start at the production phase of the materials and go along through the assembly and construction of structures.

These methods can be divided into two categories: passive methods, which are inhibition, coating, and corrosion prevention by design, and an active method which is cathodic protection.

III.2 Selection of the right material for construction

Each metal and alloy has unique and inherent corrosion behavior. Furthermore, the corrosion resistance of a metal strongly depends on the environment to which it is exposed, the chemical composition, temperature, velocity, etc.

We can define it in this rule:

$$\frac{\boldsymbol{Corrosivity\ of\ the\ environement}}{\boldsymbol{Corrosion\ resistance\ of\ the\ material}} \approx \boldsymbol{Rate\ of\ corrosive\ attack} \qquad \textbf{(III. 1)}$$

Also**,** corrosion occurs as the result of a voltage differential between two components of a system, so if a complex structure is constructed of materials that are near each other in the galvanic series, then there is a reduced likelihood of potential differences (Appendix A).

On the other hand, construction using materials that are not close in the galvanic series (such as steel and copper) can accelerate the corrosion rate **[4].**

III.3 Corrosion prevention by design

III.3.1 Deposit and impurities

The surface of the metal must be polished to avoid the formation of differential aeration cells **[7].**

III.3.2 Crevices

Crevices are formed at any point at which two metal surfaces are separated by a narrow gap, like behind spot welded overlays or bolt joints, overplayed plates, and at bolted or riveted joints. It can be avoided by avoiding edges and pockets and using fillers and mastics to fill any gaps and welded joints **[2].**

III.3.3 Inadequate drainage

Differential aeration cells are formed when droplets of water lay on the metal surface, or when there is a pocket where water can be gathered. To avoid them, there must be a drainage system **[2].**

III.3.4 Contact with wet insulation materials

Insulation materials do not cause corrosion as long as they are dry and don't contain moisture. We can avoid the wetness of the insulation by waterproofing the coating and avoiding flat horizontal surfaces **[4,7].**

III.3.5 Flowing water system

Turbulence flow will lead to erosion corrosion attack, we can avoid it by designing pipes for a smooth flow, performing regular maintenance and cleaning, and minimizing vibrations.

III.3.6 Liquid containers

It must be free of sharp corners and edges, have a smooth flow, internal and external coating, and avoid water traps **[4].**

III.4 Surface coatings

Coatings for corrosion protection can be divided into two broad groups: metallic and nonmetallic. With either type of coating the intent is the same, that is, to isolate the underlying metal from the corrosive environment.

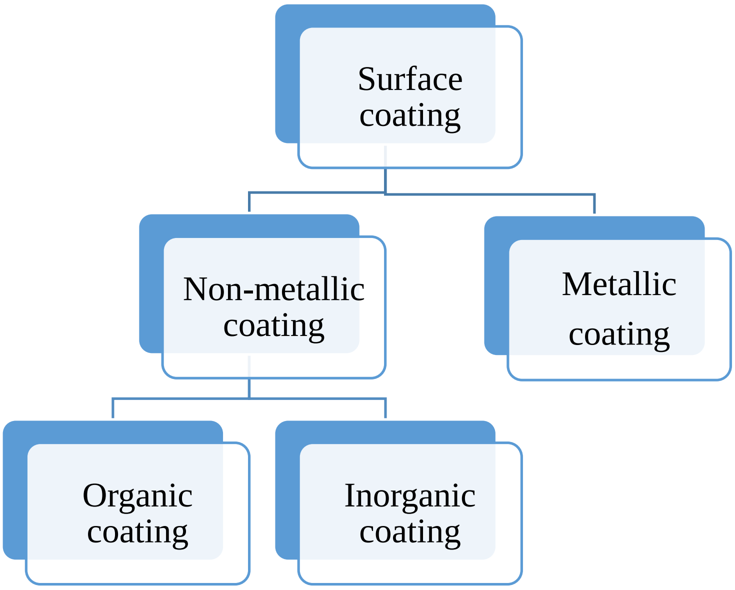

Figure III. 1 Flow chart of coating types.

III.4.1 Metallic coating

The structure is coated with a layer of another metal, which may be more noble than the structure or less noble than it.

There 3 types of metallic coating:

- **Electroplating**

The process involves depositing material using an electric current. This process results in a thin layer of metal being deposited onto the surface of a work piece called the substrate **[4].**

- **Hot dipping galvanizing**

Is the process of coating iron or steel with a layer of zinc by immersing the metal in a bath of molten zinc at a temperature of around 450 °C **[4].**

- **Thermal spray coating**

Is a process that sprays coating materials using the pressure of a high-heat gas. The material then bonds to the surface, forming a coating **[4].**

III.4.2 Non-metallic coating

III.4.2.1 Organic coating

Such as paints, coal tar, acquers, etc.

III.4.2.2. Inorganic coting

There are four methods to apply inorganic coating:

- **Oxidation**

Steel can be coated with an oxide film by heating at high temperatures, by chemical oxidation by treating steel with hot alkaline nitrate, or by anodic oxidation by making the steel structure an anode in an electrolytic cell **[4].**

- **Enamels**

Enamels are a glassy layer applied to the metal by dipping it in a suspension of powdered glass. **[6]**

- **Phosphating**

Steel is coated with a layer of iron phosphate by dipping it in a solution containing phosphoric acid and zinc phosphate **[4].**

- **Cement coating**

It is used to coat the inner side of steel pipelines carrying water or wastewater **[6].**

Figure III. 2 Cement coating for the internal surface of the pipes.

III.5 Inhibition

III.5.1 Mechanism

The inhibitor is chemically adsorbed on the surface of the metal, resulting in the formation of a protective thin film, or it can react with a potential corrosive component present in the electrolyte and, seizing its unwanted effects.

III.5.2 Classification

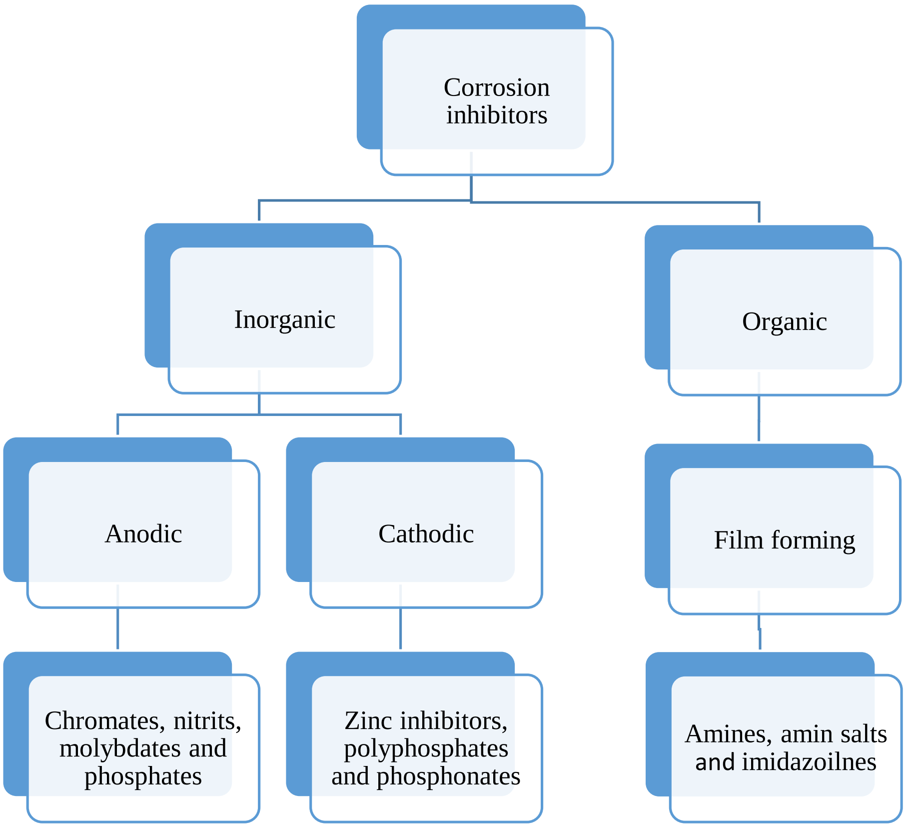

Figure III. 3 flow chart of inhibitors types.

III.5.2.1 Inorganic inhibitors

III.5.2.1.a Cathodic inhibitors

Cathodic inhibitors are chemical compounds that inhibit the cathodic reaction of the corrosion cell. Such as these compounds: $ZnSO_4$, $MgSO_4$, $Ca(HCO_3)_2$, and oxygen scavengers **[2,8].**

III.5.2.1.b Anodic inhibitors

Anodic inhibitors: are chemical compounds that inhibit anodic reaction of the corrosive cells. Compounds such as: Na_2SiO_3, Na_2CO_3, and Na_3PO_4 or Passivators **[2,8]**.

II.5.2.2 Organic inhibitors

Also called adsorption inhibitors, these are organic compounds that contain a polar group such as NH_2(an amino group). These compounds (RNH_2) adsorb on the metallic surface and isolate it from the corrosive solution (usually acids). Organic corrosion inhibitors are complex mixtures of many different molecular compounds. Organic inhibitors typically affect both anodic and cathodic areas of corrosion cells. They lay down an organic film on the entire metal surface **[2,8].**

III.6 Cathodic protection

III.6.1 Theory

Cathodic protection is a proven corrosion control method for protecting underground and undersea metallic structures, such as oil and gas pipelines, cables, utility lines, and structural foundations.

The concept of cathodic protection involves reducing the potential difference between local anodic and cathodic sites on a metal surface to zero, resulting in zero corrosion current flow. This can be accomplished by causing a current to flow onto the structure from an external anode which polarizes the cathodic sites in an electronegative direction. As the potentials of the cathodic sites polarize toward the potentials of the anodic sites, corrosion current is reduced. When the potentials of all cathodic sites reach the open circuit potential of the most active anodic sites, the voltage difference between local anodes and cathodes is eliminated, and corrosion ceases. Cathodic protection does not actually eliminate corrosion. Instead, it transfers it from the structure to the cathodic protection anode.

III.6.2 Polarization

Cathodic protection is a polarization phenomenon that refers to the shift in the electrochemical potential of a metal surface caused by the application of an external current. This shift is intended to make the metal surface more negative relative to the surrounding environment so that the metal becomes the cathode in an electrochemical cell **[3].**

A structure's potential shifts in an electronegative direction as it polarizes. The cathodic, or more positive sites polarize first as polarization happens in steps. At other sites, polarization starts as soon as the potential of the first cathodic sites reaches the potential of other sites.

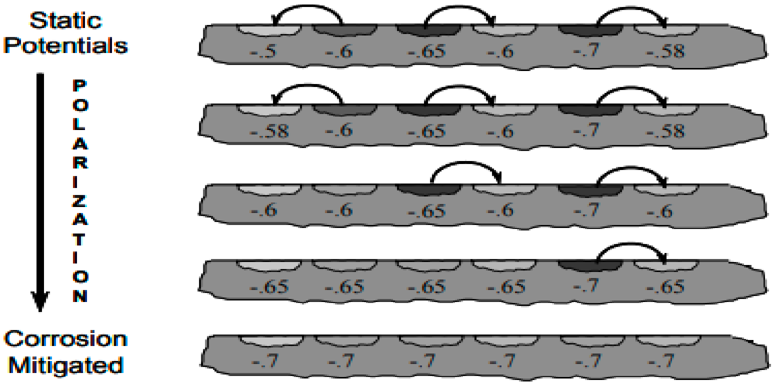

Figure III. 4 Polarization of a structure **[3].**

III.6.3 Types of cathodic protection

III.6.3.1 Sacrificial anodes

III.6.3.1.a Definition

Also known as galvanic anodes, these are materials that readily corrode and are placed in a pipe or tank with the intention of being sacrificed to corrosion, leaving the rest of the system largely corrosion-free.

The reaction mechanisms of electrochemical cells and the sacrificial anode protection device are very similar. In sacrificial anodes, the protected metal is positioned on the cathode side, and a more reactive metal or alloy is then selected and attached to the protected metal as an anode (having a greater potential difference than the protected metal). At the anode, there is an oxidation process, which results in the consumption of the sacrificed metal. The cathodic side's reduction process also takes place at the same time, shielding the protected metal from corrosion. This effectively shifts corrosion from the protected metal to the anode **[1,3,9].**

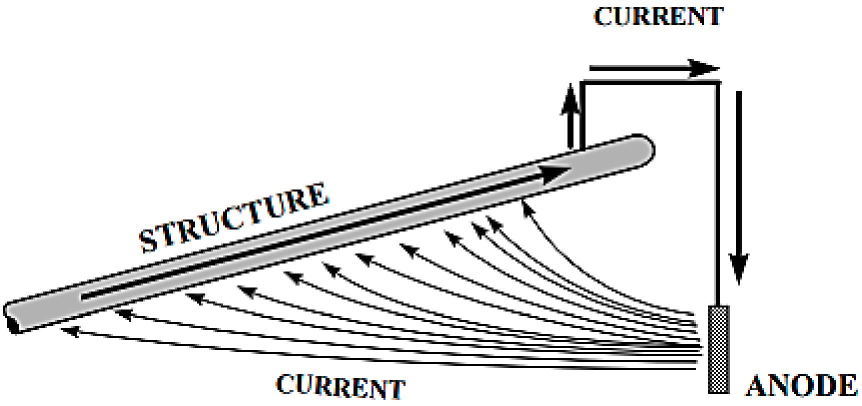

Figure III. 5 Typical galvanic anode CP system **[3].**

III.6.3.1.b Components of sacrificial anodes systems

- **Anodes**

In most cases, structures are made of steel, so the most common metals used to protect steel are magnesium, zinc, and aluminum (Appendix B). However, the pure forms of these metals can't be used because they undergo too much "self-corrosion" in the environment and do not stay active, so alloys that have been developed to stay active are used **[1,3,9]**.

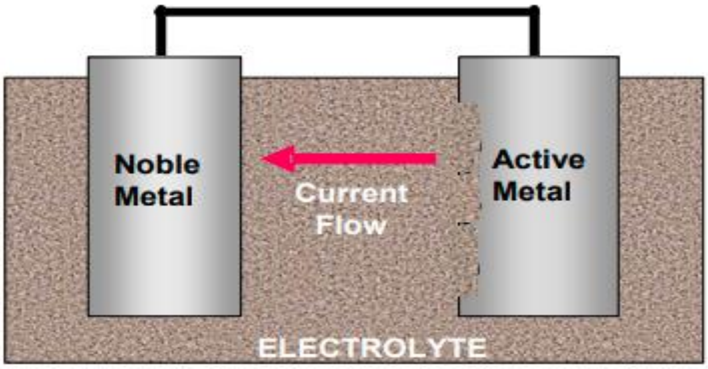

Figure III. 6 Galvanic corrosion cell **[5].**

- **Backfill**

In order to guarantee adequate electrical contact between the anode and the surrounding soil or electrolyte, backfill is the term used to refer to the material used to fill the area around the anode. The backfill material must also have good corrosion resistance and low resistivity to provide an effective corrosion protection system the primary purposes of anode backfill are:

- Provides a favorable environment to minimize earth contact resistance for the anode by being homogeneous **[1,3,9].**
- A low resistivity fill to minimize anode polarization.
- Absorption and retaining the moisture necessary for ionic conduction.

- Minimizes anode polarization by creating a favorable chemical environment.

Table III. 1 Composition of galvanic anodes backfill **[3].**

Anodes	**Magnesium anode backfill**	**Zinc anode backfill**
Ground hydrated gypsum $CaSO_4$ %	75	50
Powdered bentonite (clay)%	20	50
Anhydrous sodium sulfate Na_2SO_4%	5	0

- **Electrical wiring and attachment to the structure**

Generally, the metals used in the anodes cannot be attached to the structure by welding or bolting, so some intermediate form of metal connection is used. And this connection depends on the size of the anode:

- **Small anodes**

  Used for underground corrosion control, are connected by copper wires in their core, and must be sealed against the environment to prevent corrosion at the attachment.

- **Large anodes**

  Used in marine structures, they are directly connected to the structure and often include a cast-in core that extends beyond the anode. The cores are generally made of steel and can be welded. Mechanical forces such as debris, wave action, tidal currents, and abrasion must be taken into consideration in marine structures.

III.6.3.1.c Applications of sacrificial anodes

- Structures that require a small amount of current.
- Structures submerged in an electrolyte that has low resistivity.
- Structures with small unprotected areas, like bare metal or systems with very poor coatings.
- Isolated points that need a small amount of current in structures that use impressed current.
- Galvanic anodes can be used at the discharge point on the foreign line in instances of cathodic interference, if the circumstances are right, to return the interfering current.
- To protect underground metallic structures that are close to each other and it is challenging to install impressed current systems without running into interference issues with stray current.
- Widely used in the protection of the interior of storage tanks, vessels, and heat exchangers.
- Large anodes are used frequently in offshore structures.

III.6.3.1.d Advantages and limitations of sacrificial anodes systems

- **Advantages**
  - Little or no stray current interference because these anodes generate a small current.
  - Easy to install and no external source of current is required.
  - Uniform distribution of current.
  - Low maintenance requirements.
  - Easy to add more anodes.
- **Limitations**
  - Low efficiency in high resistivity electrolytes.
  - Replacing anodes may be difficult and costly.
  - Self-consumption is higher than impressed current anodes.
  - Many anodes are required for poorly coated structures.

III.6.3.2 Impressed current

III.6.3.2.a Definition

Impressed current is a corrosion protection system that contains anodes connected to a direct current power source. The direct current power source could be a battery, solar cells, etc. In the absence of a direct current power source, a transformer-rectifier is used to increase or decrease voltage and convert alternating current to direct current **[1,3,9].**

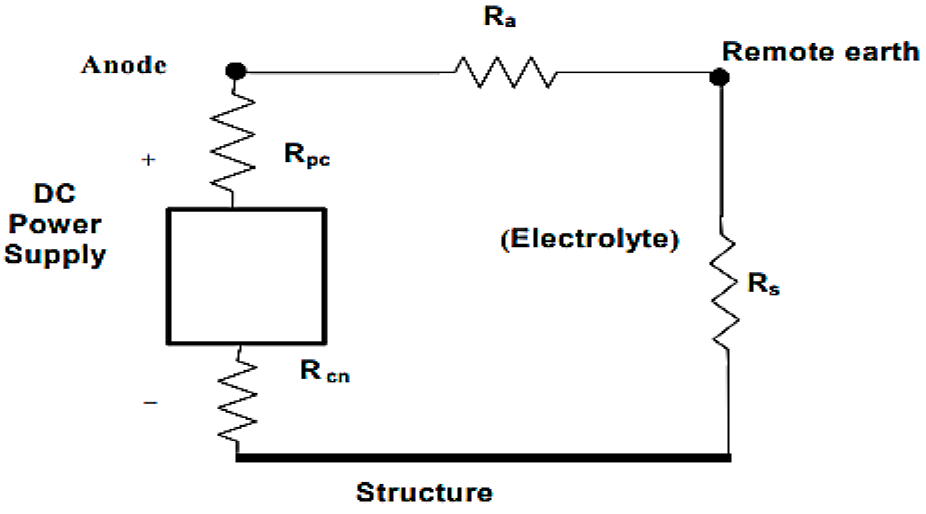

Figure III. 7 Electrical basis of impressed current cathodic protection system **[3].**

III.6.3.2.b Components of an impressed current system

- **Anodes**

Impressed current anodes, also known as impressed current cathodic protection (ICCP) anodes, are an essential component of cathodic protection systems used to prevent corrosion of metal structures (Appendix C). These anodes work by providing a protective electrical current to the structure being protected **[1,3,9].**

- **Anode Backfill**

For underground cathodic protection, carbon is used as a backfill material around impressed current anodes. The purpose of the backfill material is to:

- Reduce the resistivity of the environment surrounding the anode to increase the amount of current the anode can discharge **[1,3,9].**
- Extend the anode surface area, thus increasing the amount of current the anode can discharge.
- Reduce consumption of the anode since the carbon is consumed before the anode itself.

Carbon backfill is available in two types, calcined petroleum and metallurgical, as shown in **Table III. 2.**

Table III. 2 Impressed current anodes backfill characteristics **[3].**

Components	**Metallurgical**	**Calcined**	**Unit**
Carbon	85	99	%
Ash	8 to 10	0.1	%
Moisture	6 to 9	0	%
Sulfur	1	-	%
Volatile matter	3	0.5	%
Density	730	875-1200	kg/m^3

- **Power supply**

We can distinguish five power sources:

- **Transformer-rectifier**

The most common type of power supply used for impressed current systems is a transformer-rectifier. It’s a static electronic energy conversion device that increases or decreases voltage and transforms alternating current into direct current **[3].**

A transformer rectifier consists of:

- **AC supply**

- **Circuit breaker**

  To provide protection to the rectifier components and disconnect the AC supply when needed.

- **Transformer**

  It is a static electrical device used to step up or step down voltage, and it could also be used as an insulating device.

- **Rectifier**

  It is an electronic device that is used for converting alternating current into direct current.

- **Solar cells**

Some solar cell units are available for cathodic protection uses. Generally, these devices require an accompanying storage battery to permit continued operation during periods of no sunlight. The relatively high cost of this type of device and modest power availability limit their use, and where sacrificial anodes cannot provide the desired operating characteristics **[9].**

- **Wind Generators**

Wind-driven generators can provide cathodic protection current. Such systems generally require storage batteries and control circuits similar to solar powered systems. In the absence of AC power, wind generators may be a viable alternative energy source **[9].**

- **Thermoelectric**

Refers to a phenomenon where a temperature difference between two different materials can generate an electric potential difference, also known as a thermoelectric effect. They are not a common type of power supply for general cathodic protection use, but they can be used in some cases **[9].**

- **Batteries**

If the current requirement for a specific cathodic protection system is relatively small, it is possible to use batteries to supply the output current. A small, isolated, well-coated structure in a high-resistivity environment might use a battery power supply, perhaps in conjunction with galvanic anodes, to supply the required current output. Batteries used in cathodic protection applications should be deep-cycle batteries designed for many charge and discharge cycles.

- **Electrical cables and connections**

Electrical connections used in impressed current systems must be completely sealed with electric insulating materials to prevent intrusion of the electrolyte and must not have significant electrical resistance to avoid overheating **[3].**

In the majority of cases, copper is used for wires and cables because of the welding and brazing to a steel or iron structure, and the use of another material such as aluminum is not convenient in the field of corrosion control because it's an active metal.

Generally methods that are used in electrical distribution and connections are also used in impressed current systems.

- **To structure connection**

  Two methods are used when connecting the cathodic protection system to the structure: metallurgical bond and mechanical bond.

- **Wire-to-wire connection**

  Two methods are used in the connection of wires, metallurgical or compression connection.

- **Anode connection**

  Connection made in the anodes is usually a pressure fitting, threaded fitting, or cast lead connection.

III.6.3.2.c Applications

- Structures in need of large current requirements.
- Can be used in all electrolyte resistivities.
- For underwater components of offshore structures.
- To overcome stray current or cathodic interference problems.
- For exterior bottoms of aboveground storage tanks.
- For the protection of large heat exchanger water boxes, oil heater treaters, and other vessels.

III.6.3.2.d Advantages and limitations

- **Advantages**

- The ability to handle huge amounts of current outputs.
- The ability to adjust the amount of current generated.
- High current demands can be met with a single installation.

- Effective for high resistivity environments.
- The consumption of anodes is less than that of sacrificial anodes.
- Very convenient for protecting uncoated or poorly coated structures

- **Limitations**

- Require an external source of power.
- Continuous cost of the constant power supply.
- Risks of causing stray current interferences.
- Risks coating damage and hydrogen embritlement because of overprotection.
- More maintenance and inspection rate than the sacrificial anodes method.

III.6.4 Key differences between the two methods

Both methods of sacrificial anodes and impressed current are used to protect metal structures from corrosion, but they operate in different ways **[1,3,5,9]**, so here some key differences between the two methods:

III.6.4.1 Corrosion Mechanism

- **Sacrificial Anodes**

Sacrificial anodes operate based on the principle of galvanic corrosion. They are made of metals that are more chemically active (less noble) than the metal they are protecting. Sacrificial anodes corrode sacrificially to protect the structure. The anode material sacrifices itself by corroding preferentially, preventing corrosion of the protected metal.

- **Impressed Current Anodes**

Impressed current anodes rely on an external power source, such as a rectifier, to provide a continuous electrical current to the structure being protected. This electrical current modifies the electrochemical reactions happening at the metal surface, reducing the rate of corrosion. Impressed current anodes do not corrode sacrificially.

III.6.4.2 Anode Materials

- **Sacrificial Anodes**

Sacrificial anodes are typically made from metals that are more active (less noble) than the protected metal. Common sacrificial anode materials include zinc, aluminum, and magnesium. These materials have a higher tendency to corrode sacrificially, protecting the structure.

- **Impressed Current Anodes**

Impressed current anodes are often made from materials such as graphite, mixed metal oxides (MMO), or platinum-coated titanium. These materials are chosen for their excellent electrical conductivity and corrosion resistance. Unlike sacrificial anodes, impressed current anodes do not corrode as they provide a continuous electrical current.

III.6.4.3 Power Source

- **Sacrificial Anodes**

Sacrificial anodes do not require an external power source. They rely solely on the galvanic potential difference between the anode material and the protected metal for protection.

- **Impressed Current Anodes**

Impressed current anodes require an external power source, typically a rectifier, to supply the electrical current needed for protection. The rectifier converts alternating current (AC) to direct current (DC) and provides the necessary voltage and current output.

III.6.4.4 Lifespan and Replacement

- **Sacrificial Anodes**

Sacrificial anodes are consumed through corrosion and have a limited lifespan. They gradually diminish in size and need to be periodically replaced to maintain effective protection. The replacement frequency depends on factors such as anode material, environmental conditions, and the rate of corrosion.

- **Impressed Current Anodes**

Impressed current anodes have a longer lifespan compared to sacrificial anodes as they do not corrode sacrificially. While periodic monitoring and maintenance are necessary, the anodes themselves do not require frequent replacement.

III.6.4.5 Control and Adjustment

- **Sacrificial Anodes**

The level of protection provided by sacrificial anodes cannot be easily adjusted once they are installed. The protection level is determined by the galvanic potential difference between the anode material and the protected metal.

- **Impressed Current Anodes**

Impressed current anodes offer more control and adjustability. The output of the external power source can be adjusted to provide the desired level of protection, allowing for precise control and continuous corrosion mitigation.

III.7 Conclusion

Preventing corrosion requires understanding its causes and implementing appropriate methods to protect the materials. These measures can include selecting corrosion-resistant materials, applying protective coatings, controlling the environment (such as reducing humidity or acidity), corrosion inhibitors and, cathodic protection.

By taking proactive steps to prevent corrosion, we can extend the lifespan of materials and ensure their safe and reliable performance because the problem of corrosion can’t be solved or controlled completely.

Chapter IV

Design and realization of cathodic protection systems for fire-fighting tanks

IV.1 Introduction

Cathodic protection design is a procedure of gathering and classifying related information and calculating all needed data, with multiple objectives to achieve, such as providing sufficient current, minimizing interferences and stray currents, and providing certain flexibility to accommodate expected changes in the environment, the coating, and the operating of the system during the structure's life.

This chapter contains the design procedure of a cathodic protection system for fire-fighting tanks, and based on that design, we used MATLAB (which is a programming language specifically designed for scientific calculations) to create a SIMULINK model that can calculate all the necessary data for cathodic protection system for fire-fighting tanks. Then, using AUTOCAD (a computer-aided design software) we drew a schematic diagram and an implantation plan of cathodic protection equipment used in this project for the three tanks. Finally, we described the procedures and steps of installing cathodic protection equipment.

IV.2 Presentation of the project

IV.2.1 Description of the project

ENGCB is going to realize a project of fire-fighting tanks, networks, and automatic detection/extinguishing systems at the CC5 KENNENDA RELIZANE gas compression center.

Table IV. 1 General information of the tanks.

Protected structure	Zone	Capacity	Application of cathodic protection	Installation duration
Fire-fighting water tank (R380-B)	GZ1/GZ2 KENNENDA	2280 m^3	Internal & External	30 years
Fire-fighting water tank (R381-B)	GZ3 KENNENDA	2280 m^3	Internal & External	30 years
Fire-fighting water tank (R383-B)	OZ2 KENNENDA	8580 m^3	Internal & External	30 years

IV.2.2 Plans and datasheets of the tanks

Table IV. 2 Indication of the tanks plans symbols symbols.

Marker	**Indication**
TH1/TH2	Circular Holes for humans on the robe
TH3	Circular Holes for humans on the roof
N	Tubing for Level gauge
P	Tubing for Level Transmitter
K3/K4	Tubing for Low Level Transmitter
TPC	Cathodic protection tubing
Q	Tubing for event
A	Filling tube
G	Recycling tube
B	Tubular for product outlet with anti-vortex system
D	Purge pipe
K1/K2	Tubular for high level transmitter
C	Overflow tube
L1/L2	Reserve tube
PP	Drainage sump

IV.2.2.1 Tanks R380-B and R381-B

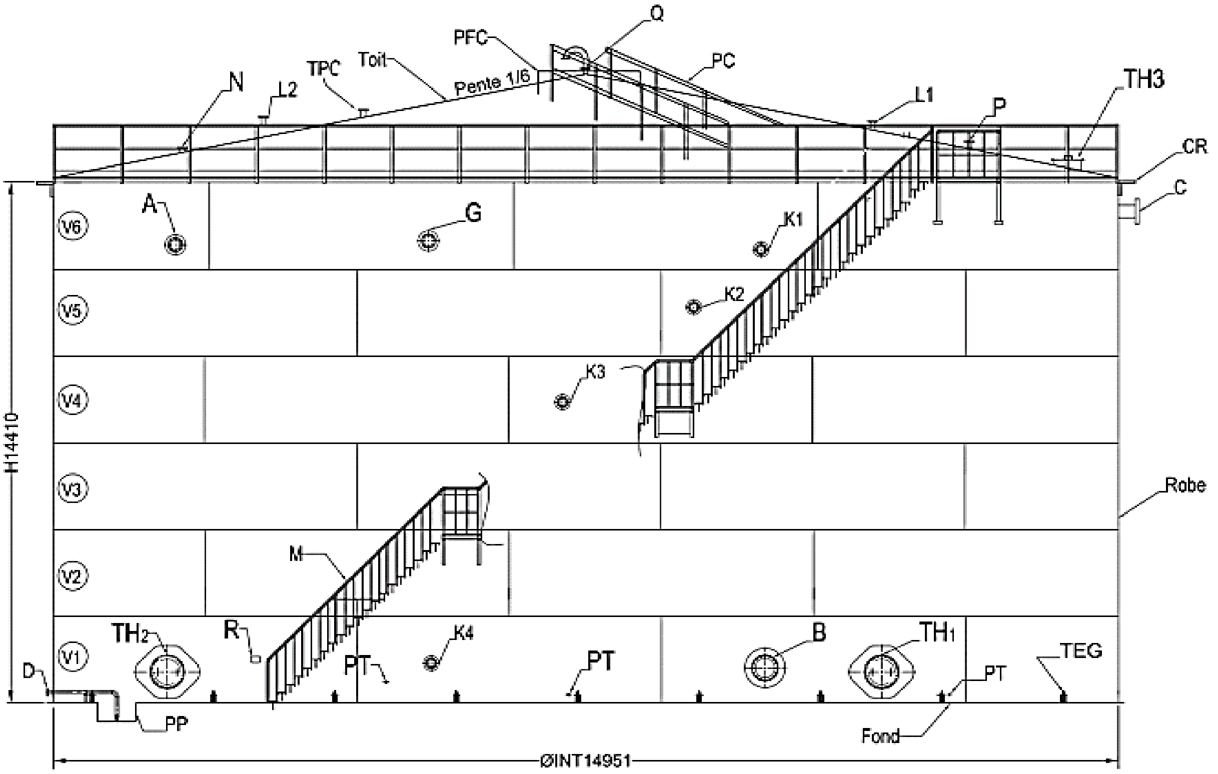

Figure IV. 1 Side view of the R380-B & R381-B tanks.

Table IV. 3 Characteristics of R380-B & R381-B tanks.

Name of the tank	**Fire-fighting tank**
Tag	R 380-B & R 381-B
Stored product	Water with a resistivity of $2\ \Omega.m$
Type of the tank	Vertical cylindrical tank with fixed roof
Quantity	2
Nominal capacity (m^3)	2258
Geometrical capacity(m^3)	2526
Internal diameter (mm)	14951
Geometrical height (mm)	14410
Useful height (mm)	12860
Implantation area	Station (GZ1, GZ2,GZ3) kenanda

IV.2.2.2 Tank 2 R 383-B

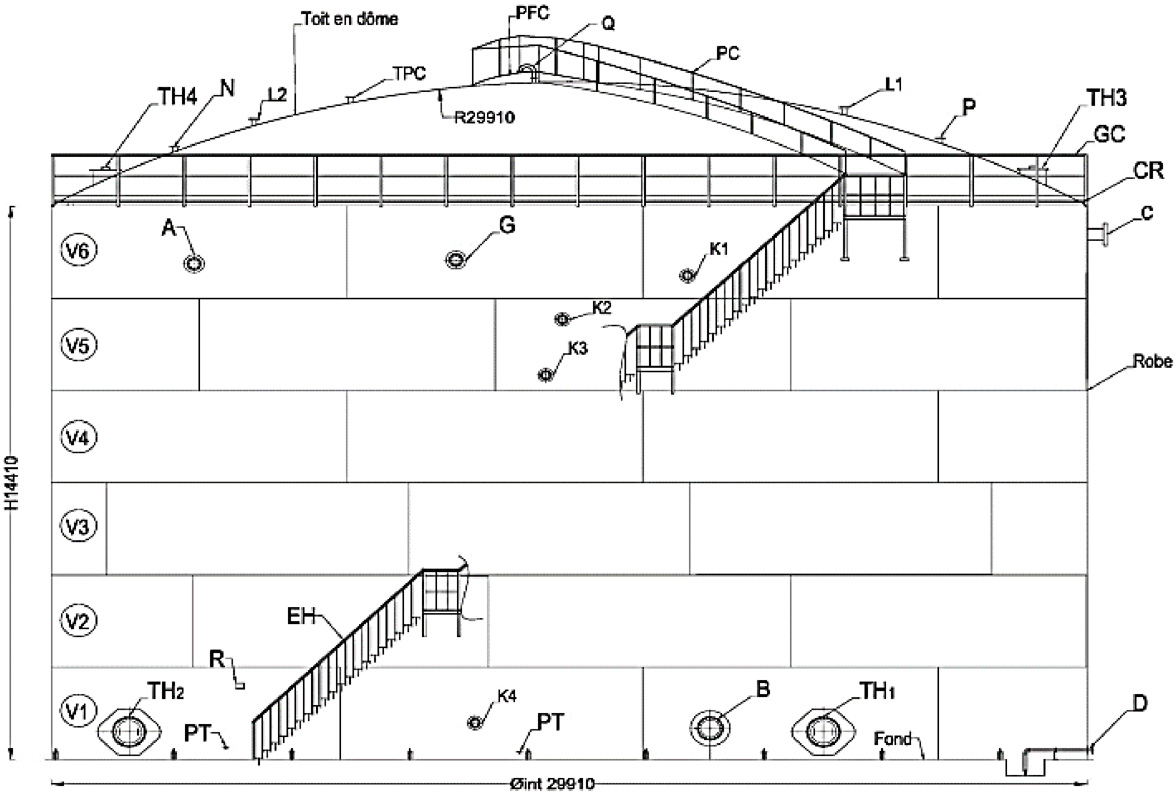

Figure IV. 2 Side view of the R383-B tank.

Table IV. 4 Characteristics of the R383-B tank.

Name of the tank	**Fire-fighting R383-B tank**
Tag	R 383-B
Stored product	Water with a resistivity of2 $\Omega.m$
Type of the tank	Vertical cylindrical tank with fixed roof
Quantity	1
Nominal capacity(m^3)	8841
Geometrical capacity (mm)	10125
Internal diameter (mm)	29910
Geometrical height (mm)	14410
Useful height (mm)	12584
Implantation area	Station OZ2 kenanda

IV.2.3 Construction material of the tanks

The tanks are made with A 283 Gr C, which is a steel alloy commonly used in various structural applications, such as buildings, bridges, machinery, and equipment. It is also used in the construction of tanks, storage vessels. Due to its moderate strength and good formability, it can be easily welded and fabricated, making it suitable for a wide range of applications.

- **Chemical Composition**

Table IV. 5 Chemical composition of A283 Gr C alloy.

Composition	**Percentage**
Carbon (C)	0.24%
Manganese (Mn)	0.90%
Phosphorus (P)	0.035%
Sulphur (S)	0.04%
Silicon (Si)	0.15-0.40%
Copper (Cu)	0.20%

- **Mechanical Properties**

Table IV 6 Mechanical properties of A283 Gr C alloy.

Mechanical property	**Value**
Tensile Strength	55,000 75,000 psi [380 - 515 MPa]
Minimal Yield Point	30,000psi [205 MPa]
Elongation in 200 mm 8"	22% min
Elongation in 50 mm 2"	25% min

IV.2.4 Coating of the tanks

IV.2.4.1 Internal coating

The whole internal surfaces of the tank are coated with a total of 650 (μm) DFT, divided into these layers:

Table IV. 7 Description of the internal coating of the tanks.

Layer	Primary	Intermediate	Final
Product	Bi-component Epoxy Protection Primer	Bi-component Epoxy primer without solvent	Bi-component Epoxy primer without solvent
DFT (μm)	50	300	300

IV.2.4.2 External coating

For the external surfaces, the bottom surface that we want to protect with cathodic protection, is left with no coating. But the walls and the top of the tank are coated with a total of 375 (μm) DFT, divided into these layers:

Table IV. 8 Description of the external coating of the tanks.

Layer	Primary	Intermediate	Final
Product	IZS/Epoxy rich with Zinc	Micaceous Iron Oxide Pigmented Polyamide Epoxy "M.I.O."	Aliphatic polyurethane
DFT (μm)	75	2x125	50

IV.3 Cathodic protection of the tanks

IV.3.1 Design of the cathodic protection system

IV.3.1.1 Descreption

The tanks are made out of steel, which can corrode when exposed to electrolytes such as soil and water. In our case, the internal surfaces are exposed to water and the external surfaces are exposed to soil, so a corrosion control method is required.

Inhibition is not used due to the hazards it pose on the environment. Coating is used for the internal surfaces, but for the external bottom surface it is not used.

For the external bottom surface of the tank, we use impressed current cathodic protection because the lifespan of the system is 30 years, and sacrificial anodes will not last that long, they need to be replaced, which is costly, not practical, and not even possible in our case, because the cathodic protection system, which is the grid, is directly under the bottom surface of the tank, so it would be impossible to reach it.

And for the internal surfaces of the tank, we also use an impressed current system with wire anodes, because the resistivity of water is very low, so the consumption rate of the anodes will be very high, and sacrificial anodes will be consumed in a short period of time compared to the lifespan of the tanks **[9-12].**

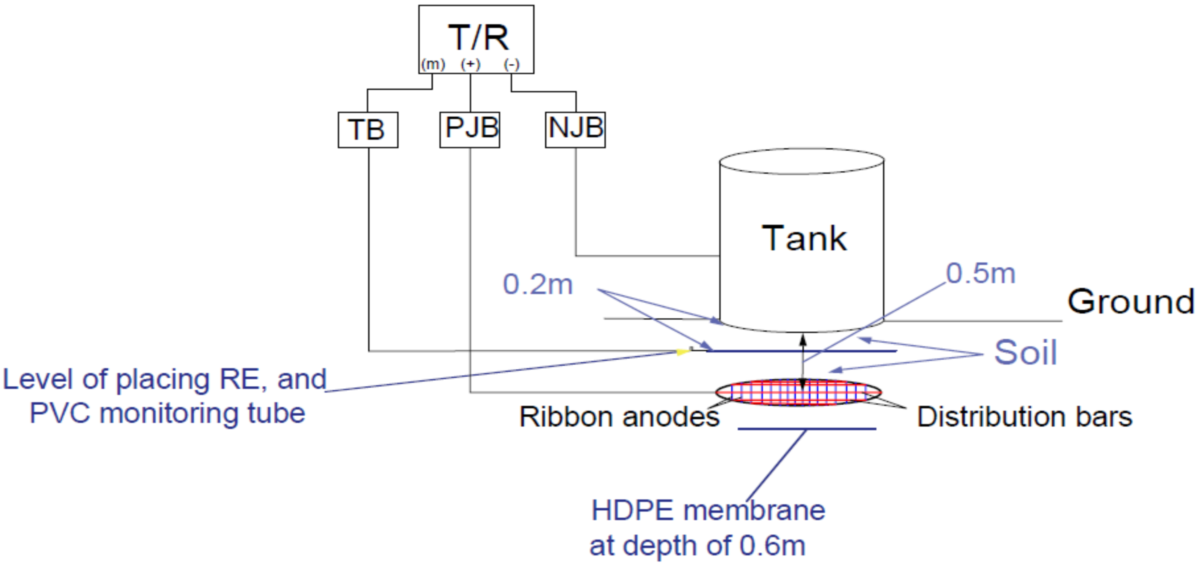

Figure IV. 3 General idea of the external protection system.

IV.3.1.2 Equipment used for cathodic protection

IV.3.1.2.a Anodes

- **Ribbon MMO anodes**

Mixed metal oxide anodes (MMO anodes) are titanium anodes coated with mixed metal oxide. It is a crystalline, electrically conductive coating that activates the titanium and allows it to function as an anode. MMO anodes have an extremely low consumption rate. They are widely used in soil, sea, mud, wastewater, and freshwater environments, etc. and they have the following advantages:

- Light weight.
- High chemical stability, even in environments with very low PH values.
- The oxide coating of mixed metal anodes is not affected by chlorine.
- The rate of MMO anode wear is extremely low and uniform. (1 to 6 $mg/A \times year$).
- The MMO anodes can be operate at high current density.

Table IV. 9 **Characteristics** of MMO ribbon anodes.

Characteristics	Value	Unit
Width	6.35	mm
Thickness	0.635	mm
Linear resistance	0.138	Ω/m
Angle of protection	60	°
Linear weight	0.018	kg/m
Current output per linear meter for a current density of 3 A/m^2	42	mA/m
The life span for a current density of 3 A/m^2	50	years
Depth of burial	0.3	m

- **Wire MMO anodes**

The MMO wire anodes consists of a solid titanium wire with a mixed metal oxide coating and have the following characteristics:

Table IV. 10 Characteristics of MMO wire anodes.

Characteristics	Value	Unit
Diameter	0.0015	m
Output current for temperatures between 5℃ to 70℃	100	A/m^2
Output current per linear meter	0.3	A/m
Resistance of wire anodes per meter	0.022	Ω
Lifespan	20	$years$
Consumption	0.5 to 4	$mg/A.year$

- **Distribution bars**

The distribution bars are made of Titanium and have the following characteristics:

Table IV. 11 Charcteristiques of distribution bars.

Characteristiques	Value	Unit
Width	12.7	mm
Thickness	0.9	mm
Linear resistance	0.043	Ω/m
Weight	0.0512	kg/m
Equivalent diameter	8.72	mm

IV.3.1.2.b Reference electrodes

- **Copper copper sulfate reference electrode**

The copper-copper sulfate reference electrode consists of a copper wire or bar immersed in a saturated aqueous solution of copper sulfate. The potential of this reference electrode at 25°C, is $+316mV$ compared to the NHE (Normal Hydrogen Electrode). Like all reference electrodes, the electrolytic junction with the aqueous medium is realized by means of a porous wall (sintered).

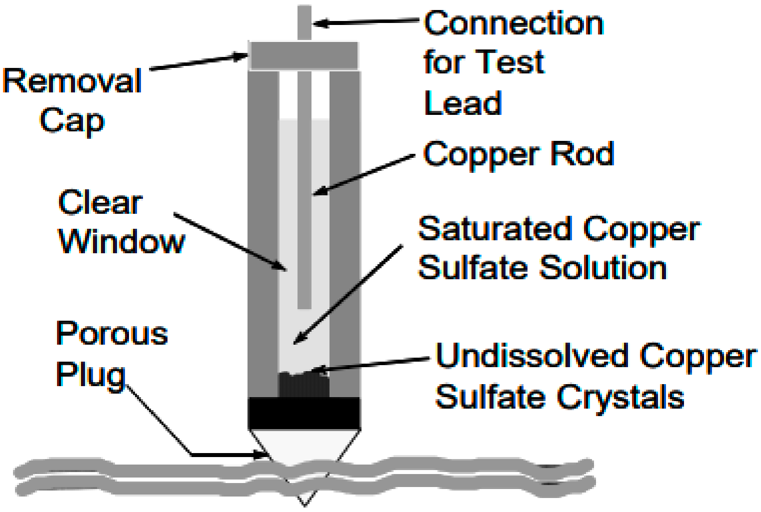

Figure IV. 4 Components of copper copper sulfate reference electrode **[3].**

- **Silver silver chloride reference electrode**

The silver-silver chloride reference electrode consists of a silver wire coated with silver chloride immersed in a chloride solution. The potential of this electrode depends on the concentration (activity) of ions, in the presence of saturated potassium chloride it is $+195mV$ compared to the NHE (Normal Hydrogen Electrode) at 25°C. In seawater, it is $+250mV$ compared to NHE.

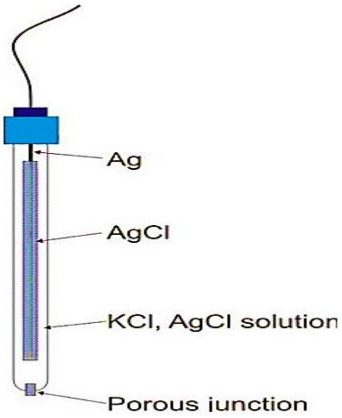

Figure IV. 5 Components of silver silver chloride reference electrode **[3].**

IV.3.1.2.c Transformer/rectifier

Impressed current cathodic protection systems use an external power source, which is a transformer/rectifier, with an AC input and an adjustable DC output to the structure to be able to respond to variations in cathodic protection demands throughout the life of the system and The life span of the transformer/rectifier must be superior or equal to the life span of the structure. The efficiency of the T/R must be 80% of its complete performance, and the voltage and the current of the T/R can be regulated from 0% to 100%.

Oil-bath transformers that are used in this application are ONAN types. The transformer, the rectifier bridge, and the control unit are immersed in oil for cooling, and the other components are air-cooled.

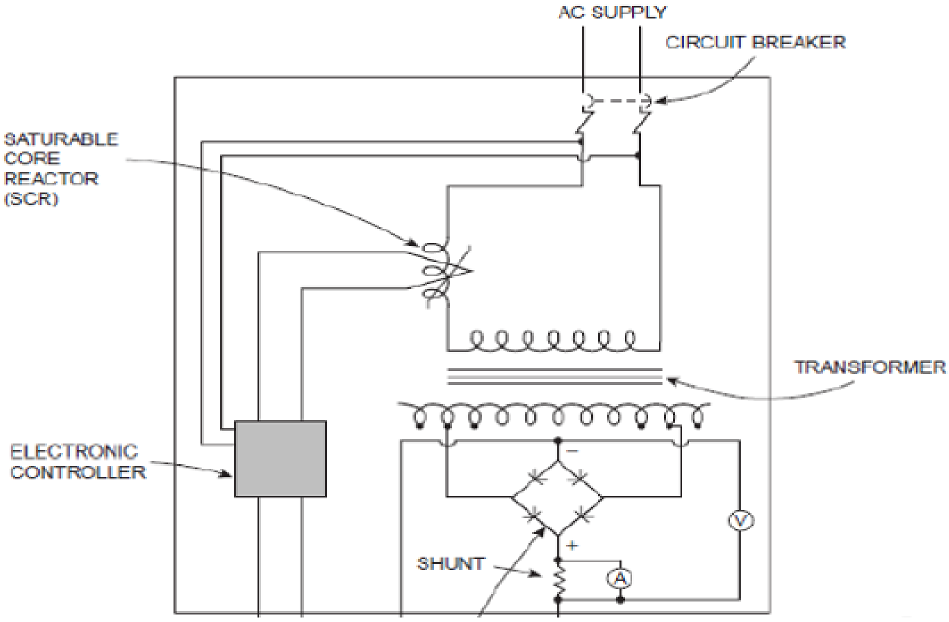

Figure IV. 6 Typical diagram of a constant potential rectifier.

IV.3.1.2.d Polarizing Cell Replacement

The Polarization Cell Replacement (PCR) is a solid-state device designed to simultaneously provide DC decoupling and AC continuity/grounding when used with catholically protected structures, such as pipelines, tanks, grounding systems, and cable casings. Commonly used to decouple electric equipment from grounding systems, for AC Mitigation projects, or other isolation and grounding applications, the PCR provides safety grounding while also isolating the catholically protected structure, improving CP system performance.

Table IV. 12 Charcteristiques of polarization cells.

Life span	**30 years**
Application	grounding
Material	316L stainless steel or equivalent
DC blocking voltage	-3 V / +1 V
Operating temperature	-40 °C / + 65 °C
Protection type	IP54

IV.3.1.2.e Isolation joints

Isolation joints are used to separate different metallic section in the same structure, so the protection current will not flow from the protected sections to the isolated sections. Also stopping current interferences from railways or other structures from interfering with the cathodic protection current. Another use of isolation joints is to stop galvanic corrosion from happening in the case of dissimilar metals in contact.

In our case it’s used to separate the protected sections of the tank from the pipes carrying water for proper use.

Table IV. 13 Characteristics of isolation joints.

Life span	**30 years**
Application	Stopping protection current from entering non protected surfaces
Isolation resistance	40000 MΩ
Protection type	IP54

IV.3.1.2.f Spark gaps

Used to protect isolation joints from high voltages.

Table IV. 14 Characteristics of spark gaps.

Life span	**30 years**
Application	Protection of isolation joints
Ignition voltage	< 1.2 KV
Ignition voltage at pulses	2.2 KV
Operating temperature	-20°C à +80 °C
Protection type	IP54

IV.3.1.2.g Anti-lightning system

- **lightning rod**

Which is placed at the highest point of the tank to provide a preferred path for lightning strikes. And they are designed to attract lightning and safely conduct the electrical current to the ground.

- **Down Conductors**

Down conductors are metal conductors that connect the lightning rods to the grounding system. They provide a low-resistance path for the lightning current to flow downward, away from the tank.

- **Grounding System**

The grounding system plays a crucial role in dissipating the lightning current into the ground safely. It consists of grounding electrodes, buried in the earth near the water storage tank. The lightning rods and down conductors are connected to the grounding system to facilitate the dissipation of the electrical energy.

IV.3.1.2.h Connection cables

The choice of the type of cable essentially comes down to the calculation of the cross-section and the choice of the degree of insulation according to Conditions of use such as:

- The intensity of the transported current.
- The length of the link (voltage drop).
- Temperature of use (heating of the core).
- The nature of the installation.

The connecting cables are made of PVDF/HMWPE and have the following characteristics:

Table IV. 15 Characteristics of connection cables.

Section (mm^2)	16	35	50
Linear resistance (Ω/km)	1.15	0.727	0.524

IV.3.1.2.i Power supply connectors of the ribbon anodes

The titanium strip welded to a 3 mm diameter x 100 mm long titanium wire, the encapsulation of the DC cable will be done by connection kit.

Table IV. 16 Dimensions of power supply connectors.

Dimensions	**Value**	**Unit**
Width	0.0127	m
Thickness	0.0009	m
Length	0.1	m

IV.3.1.2.j HDPE membrane

It is a type of high-density polyethylene material that is used as a barrier or liner in various applications for waterproofing, containment, and electrical isolation purposes. In our case it is used to eliminate any current interferences.

IV.3.1.2.k Spot welder

Resistance spot welding should be used to weld the MMO coated anode ribbon bar. A water cooler shall be provided which may or may not need to be used depending on the production rate of the weld.

IV.3.1.2.l Junction boxes

The cathodic protection system uses an external power supply. A transformer rectifier (T/R), fed by an external source of alternating current. The DC output of the TR is adjustable to meet the variations of the cathodic protection current demands throughout the life of the system. The negative pole of the DC output of the TR is connected to a negative junction box the positive pole of the DC output of the TR is connected to a positive junction box.

The performance of the cathodic protection system and the adjustments that will be necessary throughout the life of the project require the connection of coated electrical cables on the structures to be protected. The other end of these cables will be connected to a test box or measuring point (TB) installed in the vicinity of the structure.

The general structure of the PJB, NJB and TB, the fixations, the auxiliary material must be designed in a robust way to withstand all shocks during transport, installation and operation. Joints and fastening materials shall be sufficiently strong and well protected to prevent damage and/or leakage.

Table IV. 17 Charactrsitiques of NJB, PJB and TB.

Item	NJB	PJB	TB
Application	Cathode junction	Anode junction	Potential measurement
Life span (years)	30	30	30
Protection class	IP55	IP55	IP55
Resistance to mechanical impacts	IK10	IK10	IK10
Material	316L stainless steel	316L stainless steel	316L stainless steel

IV.3.1.2.m Splicing kit

It contains:

- Impact resistant polycarbonate casting mold.
- Hydrolysis resistant polyurethane resin and hardener.
- Offset Funnel and sealing tape.

IV.3.1.3 Design criteria

For any metal, its energy level is highest when it is new, Laboratory measurements of new steel samples in many different soil environments have indicated the most active corrosion potential is between −850 mV and −1200 mV both referenced to a saturated copper-copper sulfate reference electrode.

IV.3.1.3.a Potential criteria of the external bottom surface

All potentials are given with relation to a reference electrode saturated with copper/copper sulfate (Cu/CuSO4).

Table IV. 18 Cathodic protection criteria for external cathodic protection system.

Minimum potential of the external bottom of the tanks	-0.85	*V*
Maximum potential of the external bottom of the tanks	-1.2	*V*

IV.3.1.3.b Potential criteria of the internal walls and bottom surface

All potentials are given with relation to a reference electrode saturated with silver/silver chloride Ag/Ag Cl.

Table IV. 19 Cathodic protection criteria for internal cathodic protection system.

Minimum potential of the internal bottom and walls of the tanks	-0.85	*V*
Maximum potential of the internal bottom and walls of the tanks	-1.2	*V*

IV.3.1.4 Mathematical equations of CP design

IV.3.1.4.a External protection equations

- **Soil resistivity**

To calculate the soil resistivity we use the Wenner method. This method is used to determine the resistivity of soil within an area. The Wenner procedure involves driving four metallic pins into the earth, in a straight line, equally spaced. The pin spacing is equal to the depth of investigation of the average soil resistivity.

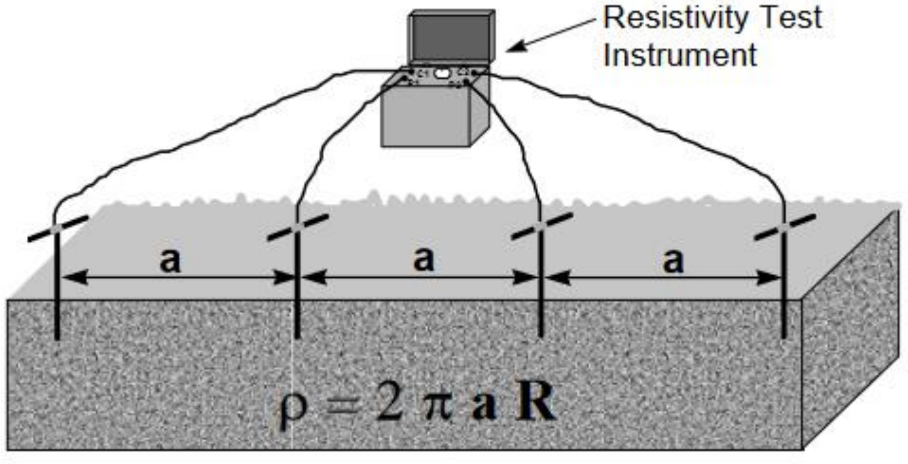

Figure IV. 7 Demonstration of the 4 pins Wenner method **[3]**.

We apply current between the center two pins, then we measure the voltage drop between these two pins, then we use ohm law to determine the resistance.

$$U = R \times I \tag{IV. 1}$$

$$R = \frac{U}{I} \tag{IV. 2}$$

U : Voltage drop between two pins (V).

R : Resistance between of the soil between two pins (Ω).

I : Current applied between two pins (A).

The soil resistivity is a function of current, resistance and spacing between the pins which is also the depth of the test which can be written as follows:

$$\rho = 2 \times \pi \times a \times R \tag{IV. 3}$$

ρ : Soil resistivity ($\Omega . m$)

π : Constant Pi= 3.14.

a : Spacing between two pins.

R : Resistance between of the soil between two pins (Ω).

- **Surface to be protected**

We are going to calculate only the surface of the bottom of the tank, because it is the only external part in contact with the soil.

$$S = \frac{\pi}{4} \times D^2 \qquad \textbf{(IV. 4)}$$

S : Surface to be protected (m^2).

D : Diameter of the tank (m).

π : Constant of pi= 3.14.

- **Current density**

Calculation of current density needed by the external surface of the tank depends on the operating temperature of the tank. For the temperature of 30°C the current density required by bare steel is $0.02A/m^2$ **[13]**, and the current density of bare steel increases by 25% for each 10°C increase in temperature above 30°C.

$$i = i_0 + \frac{25}{100} \times \frac{(T-30)}{10} \times i_0 \qquad \textbf{(IV. 5)}$$

i : Current density (A/m^2).

i_0 : Current density at 30°C (A/m^2).

T : Operating temperature (°C).

- **Protective current requirement**

Now we can calculate the amount of current needed for protecting the external surface of the bottom of the tank:

$$I = \frac{S \times i}{1000} \qquad \textbf{(IV. 6)}$$

I : Current requirement (A).

S : Surface to be protected (m^2).

i : Current density (A/m^2).

- **Minimal anodes quantity needed**

$$L_{min} = \frac{I}{I_s} \qquad \textbf{(IV. 7)}$$

L_{min} : Minimal length of anodes (m).

I : Current requirement (A).

I_s : Current output of the anodes MMO = $0.042A/m$.

- **Spacing between the anodes**

$$L = 2 \times d \times tan\theta \qquad \textbf{(IV. 8)}$$

L : Spacing between the anodes (m).

d : Depth of burial (m).

θ : Angle of protection of the anode (°).

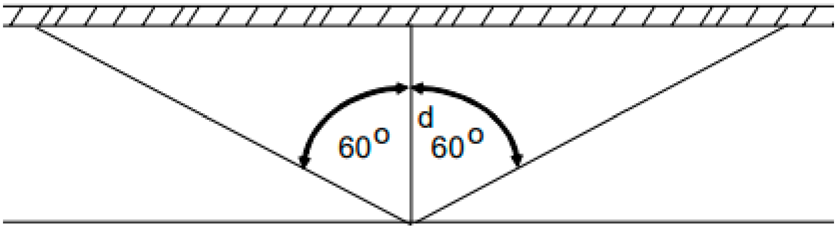

Figure IV. 8 Surface protected by a single ribbon anode **[10].**

- **Anode Length Required Based On Spacing between anodes**

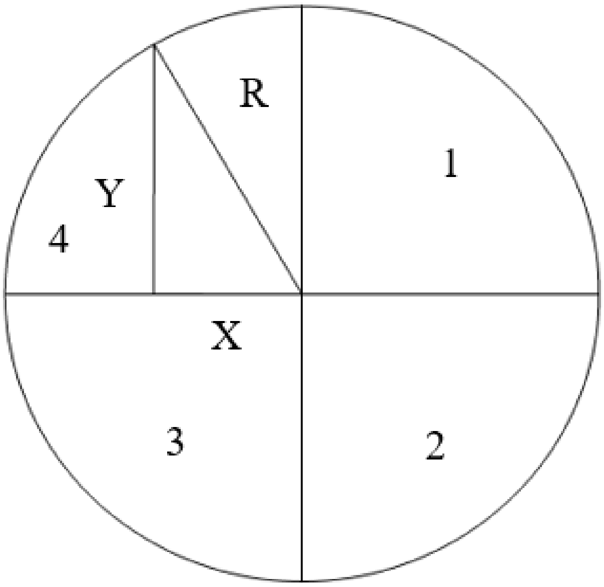

Figure IV. 9 The circle of ribbon anodes and distribution bars placement.

We are going to leave a spacing of 0.5 meters from one side of the bottom of the tank, then we will place our first anode which is Y, and we are going to calculate its length by the Pythagorean Theorem. Then we will leave a spacing of 1 meter as we found earlier, and we will place the second anode until we reach a length of 0.5 meter of the other side of the tank

$$y_a = \sqrt{R^2 - (X_a)^2} \quad \textbf{(IV. 9)}$$

y_a : Length of ribbon anode in a single quadrant of the circle (m).

R : Bottom radius of the tank (m).

X_a : Spacing between anodes (m).

- **Ti conductors length required**

The same procedure used for the placement of the anodes can be used here, but with a spacing of 3 meters between the distribution bars

$$y_b = \sqrt{R^2 - (X_b)^2} \qquad \textbf{(IV. 10)}$$

y_b: Length of distribution bars in a single circle quadrant (m).

R: Bottom radius of the tank (m).

X_b: Spacing between the distribution bars.

- **Average Resistance of ribbon anodes**

$$R_a = \frac{\rho}{2 \times L_m \times \tan\theta} \times [\ln(\frac{2 \times d \times tan\theta}{l})] \qquad \textbf{(IV. 11)}$$

R_a: Average anode resistance (Ω).

ρ: Soil resistivity ($\Omega . m$).

d: Depth of burial (m).

θ: Angle of protection for the anode.

L_m: Average length of an anode (m).

l: Width of the ribbon anode (m).

- **Total resistance of ribbon anodes**

$$R_T = \frac{R_a}{N} \qquad \textbf{(IV. 12)}$$

R_T: Total resistance of the ribbon anodes (Ω).

R_a: Average anode resistance (Ω).

N: Total number of anodes.

- **Average distribution bars resistance**

$$R_{cn} = R_C^1 \times L_{mTi} \qquad \textbf{(IV. 13)}$$

R_{cn} : Average distribution bars resistance (Ω).

R_C^1: Linear resistance of the distribution bar ($\Omega . m$).

L_{mTi}: Average length of the distribution bar (m).

- **Total resistance of distribution bars**

$$R_{TTi} = \frac{R_{cn}}{W} \qquad \textbf{(IV. 14)}$$

R_{TTi}: Total resistance of distribution bares (Ω).

R_{cn} : Average distribution bars resistance (Ω).

W: Total number of distribution bars.

- **Total resistance of the cables**

$$R_{cables} = \frac{R_{16} \times L_{16}}{N_{16}} + \frac{R_{35} \times L_{35}}{N_{35}} + \frac{R_{50} \times L_{50}}{N_{50}} \tag{IV. 15}$$

R_{cables}: Total resistance of the cables (Ω).

R_{16}: Linear resistance of the cables 16 mm^2 (Ω).

R_{35}: Linear resistance of the cables 35 mm^2(Ω).

R_{50}: Linear resistance of the cables 50 mm^2(Ω).

L_{16}: Length of one 16 mm^2 cable (m).

L_{35}: Length of one 35 mm^2 cable (m).

L_{50}: Length of one 50 mm^2 cable (m).

N_{16}: Total number of 16 mm^2 cables.

N_{35}: Total number of 35 mm^2 cables.

N_{50}: Total number of 50 mm^2 cables.

- **Total resistance of the circuit**

$$R_{Circuit} = R_{CT} + R_T + R_{TTi} \tag{IV. 16}$$

$R_{Circuit}$: Total resistance of the circuit (Ω).

R_{cables}: Total resistance of the cables (Ω).

R_T: Total resistance of the ribbon anodes (Ω).

R_{TTi}: Total resistance of distribution bares (Ω).

- **Minimal current**

$$I_m = I \times 1.2 \tag{IV. 17}$$

I_m: Minimal current of protection (A).

I: Current requirement (A).

- **Minimal voltage**

$$U_m = (I_m \times R_{Circuit}) + EMF \tag{IV. 18}$$

U_m: Minimal voltage of the circuit(V).

I_m: Total required current (A).

$R_{Circuit}$: Total resistance of the circuit (Ω).

EMF: Counter Electromotive Force(V).

- **The attenuation of current in the ribbon anodes**

$$I_R = cosh\sqrt{\frac{R_{int}}{R_{ext}}} \qquad \textbf{(IV. 19)}$$

I_R: Current loss (%)

R_{int}: Internal resistance of ribbon anodes (Ω).

R_{ext}: External resistance of ribbon anodes in reference to the soil (Ω).

- **Internal resistance of the ribbon anodes**

$$R_{int} = \frac{\beta \times L}{A} \qquad \textbf{(IV. 20)}$$

R_{int}: Internal resistance of ribbon anodes.

β: Ribbon anodes resistance= $0.427\mu.\Omega.m$.

L: Length of the anode (m).

A: Surface of the anode (m^2).

- **Resistance of an anode between two distribution bars**

$$R_{am} = \frac{\rho}{2 \times L_D \times \tan\theta} \times [\ln(\frac{2 \times d \times \tan\theta}{l})] \qquad \textbf{(IV. 21)}$$

R_{am}: Anode resistance (Ω).

ρ: Soil resistivity ($\Omega.m$).

d: Depth of burial (m).

θ: Angle of protection for the anode.

L_D: Length of the anode between two distribution bars.

l: Width of ribbon anodes.

- **External resistance of the ribbon anodes**

$$R_{ext} = \frac{R_{am}}{N} \qquad \textbf{(IV. 22)}$$

R_{ext}: External resistance of the anode (Ω).

R_{am}: Anode resistance (Ω).

N: Number of anodes.

- **Voltage attenuation**

$$U_r = \frac{I_a \times \rho}{2 \times \pi \times L} \times \ln(\frac{\sqrt{d^2+r^2+(\frac{L}{2})^2}+\frac{L}{2}}{\sqrt{d^2+r^2+(\frac{L}{2})^2}-\frac{L}{2}}) \qquad \textbf{(IV. 23)}$$

U_r: Potential at a given distance r (V).

ρ: Soil resistivity $(\Omega.m)$.

d: Depth of burial (m).

r: Distance between the anode and structure (m).

I_a: Current output of the ribbon anode (A/m).

L: Spacing between two anodes (m).

r: Distance between the anode and structure (m).

- **Verification of the anode's life span**

$$i'_a = \frac{I}{S_a} \tag{IV. 24}$$

$$\log(t) < 3.3 - \log(i'_a) \tag{IV. 25}$$

i'_a: Current density of the anode.

I: Current requirement (A).

S_a: Total surface of the ribbon anode.

t: Life span

IV.3.1.4.b. Internal protection equations

- **Surface to be protected**

We are going to calculate both the wetted and bottom surface of the tank:

$$S = \frac{\pi}{4} \times D^2 + (\pi \times D \times H) \tag{IV. 26}$$

S: Surface to be protected (m^2).

D : Diameter of the tank (m).

H: Wetted height of the tank (m).

- **Current density**

$$i = i_0 + \frac{25}{100} \times \frac{(T-30)}{10} \times i_0 \tag{IV. 27}$$

i: Current density (mA/m^2).

i_0: Current density at 30°C (mA/m^2) which is $i_0 = 0.002 A/m^2$ **[13].**

T: Operating temperature (°C).

- **Protective current requirement**

$$I = S \times i \times f_{deterioration} \tag{IV. 28}$$

I: Current requirement (A).

S: Surface to be protected (m^2).

i: Current density (mA/m^2).

$f_{deterioration}$: Deterioration factor of the internal surface coating%.

- **Minimal quantity requirement of anodes**

$$L_{min} = \frac{I}{I_s} \tag{IV. 29}$$

L_{min}: Minimal length of anodes (m).

I: Current requirement (A).

I_s : Current output of the anodes MMO = 42mA/m.

- **Radius of the first series of string of anode wire**

$$r_a = \frac{(D \times N)}{2 \times (\pi + N)} \tag{IV. 30}$$

r_a: Radius of the first series of string of anode wire (m).

D: Diameter of the tank.

N: Number of anode wire strings.

- **Circumferential distance between the anodes**

$$d_a = \frac{(2 \times \pi \times r_a)}{N} \tag{IV. 31}$$

d_a: Circumferential distance between the anodes (m).

r_a: Radius of the first series of string of anode wire (m).

N: Number of anode wire strings

- **Distance from the anode to the tank wall and the bottom of the tank**

$$d_s = \frac{d_a}{2} \tag{IV. 32}$$

d_s: Distance from the anode to the tank wall and the bottom of the tank (m).

d_a: Circumferential distance between the anodes (m).

- **Resistance of the anodes**

$$R_a = \left(0.366 \times \frac{\rho}{L}\right) \times \left(log\left(\frac{D}{f_c \times r_a}\right)\right) \tag{IV. 33}$$

R_a: Resistance of the anodes.

ρ: Water resistivity.

D: Diameter of the bottom of the tank (m).

f_c: Correction factor.

r_a: Radius of the first series of string of anode wire (m).

L: Length of a single string of anode wire (m).

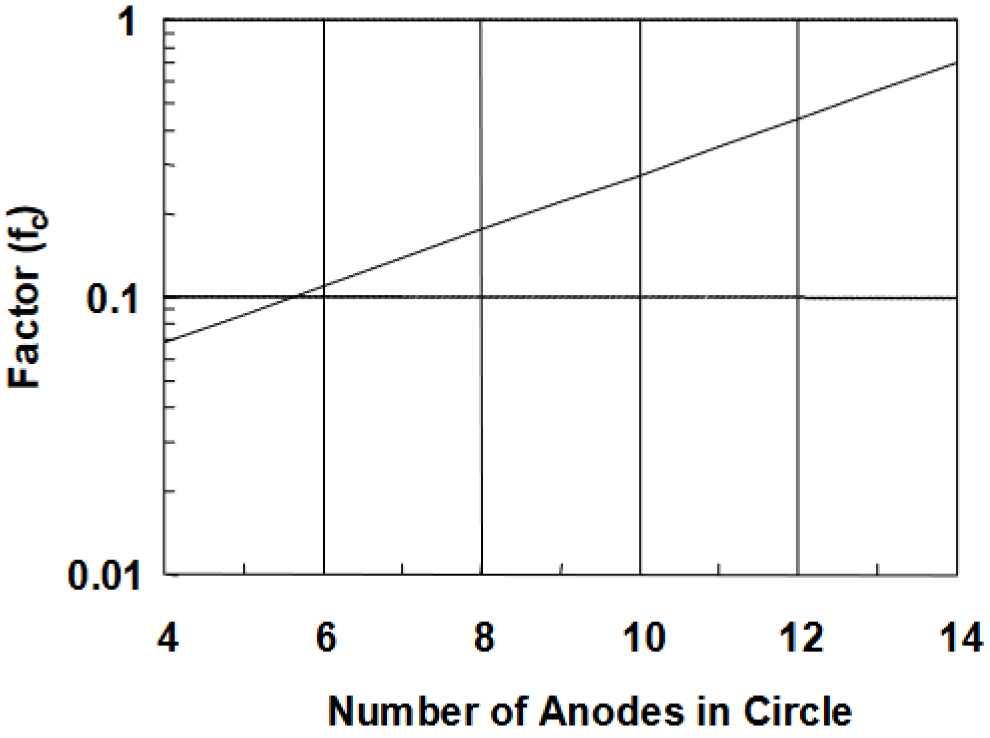

Figure IV. 10 Correction factor for number of anodes **[10].**

After we find the appropriate number of anodes we extract the correction factor from the diagram in figure IV.

- **Resistance of the cables**

$$R_{cables} = \frac{R_{16} \times L_{16}}{N_{16}} + \frac{R_{35} \times L_{35}}{N_{35}} + \frac{R_{50} \times L_{50}}{N_{50}} \qquad \textbf{(IV. 34)}$$

R_{cables}: Total resistance of the cables (Ω).

R_{16}: Linear resistance of the cables 16 mm^2 (Ω).

R_{35}: Linear resistance of the cables 35 mm^2(Ω).

R_{50}: Linear resistance of the cables 50 mm^2(Ω).

L_{16}: Length of one 16 mm^2 cable (m).

L_{35}: Length of one 35 mm^2 cable (m).

L_{50}: Length of one 50 mm^2 cable (m).

N_{16}: Total number of 16 mm^2 cables.

N_{35}: Total number of 35 mm^2 cables.

N_{50}: Total number of 50 mm^2 cables.

- **Resistance of the anode material for** 55℃

$$R_{55℃} = \frac{R_{18℃} \times 55℃}{18℃} \qquad \textbf{(IV. 35)}$$

$R_{55℃}$: Resistance of the anode wire at the temperature55℃ .

$R_{18℃}$: Resistance of anode wire at the temperature18℃.

- **Resistance of the anode material**

$$R_e = \frac{R_{55℃} \times L_{wire}}{N} \qquad \textbf{(IV. 36)}$$

R_e: Resistance of the anode material (Ω).

$R_{55℃}$: Resistance of the anode wire at the temperature55℃.

L_{wire}: Length of a single anode wire.

N: Total number of anodes.

- **Total resistance of the circuit**

$$R_{circuit} = R_{CT} + R_{at} + R_e \qquad \textbf{(IV. 37)}$$

$R_{circuit}$: Total resistance of the circuit (Ω).

R_{CT}: Total resistance of the cables (Ω).

R_{at}: Total resistance of the anodes (Ω).

R_e: Resistance of the anode material (Ω).

- **Minimal current**

$$I_m = I \times 1.2 \qquad \textbf{(IV. 38)}$$

I_m: Minimal current of protection (A).

I: Current requirement (A).

- **Minimal voltage**

$$U_m = (I \times R_{circuit}) + FCE \qquad \textbf{(IV. 39)}$$

U_m: Minimal voltage (V).

I: Total current required (A).

$R_{circuit}$: Total resistance of the circuit (Ω).

FCE: Counter Electromotive Force(V).

IV.3.1.5 Characteristics of the tanks, input data and initial results

Table IV. 20 Results of soil resistivity.

Results	Value	Unit
Voltage	12	V
Current	2.3	A
Resistance	5.175	Ω
Spacing between two pins	4	m
Soil resistivity	130	$\Omega.m$

Table IV. 21 Anodes placement results of R-380-B and R-381-B tanks.

N	Spacing $X(m)$	Radius $R(m)$	Length $Y(m)$	Quadrant	Total (m)
1	0.5	7.5	7.48	4	29.93
2	1.5	7.5	7.35	4	29.39
3	2.5	7.5	7.07	4	28.28
4	3.5	7.5	6.63	4	26.53
5	4.5	7.5	6	4	24
6	5.5	7.5	5.1	4	20.4
7	6.5	7.5	3.74	4	14.97
8	7.5	0	15	1	15
Total length of ribbon anodes required					188.51
5%additional					9.43
Total length after the addition					197.18

Table IV. 22 Distribution bars placement results for R380-B and R381-B tanks.

N	Spacing $X(m)$	Radius $R(m)$	Length $Y(m)$	Quadrant	Total (m)
1	1.5	7.5	7.35	4	29.39
2	4.5	7.5	6	4	24
3	7.5	0	15	1	15
Total length of distribution bars required					68.39
5%additional					3.42
Total length after the addition					71.81

Table IV. 23 Anodes placement results of R383-B.

N	Spacing $X(m)$	Radius $R(m)$	Length $Y(m)$	Quadrant	Total (m)
1	0.5	15	14.99	4	59.97
2	1.5	15	14.92	4	59.7
3	2.5	15	14.79	4	59.16
4	3.5	15	14.59	4	58.34
5	4.5	15	14.31	4	57.24
6	5.5	15	13.96	4	55.82
7	6.5	15	13.52	4	54.07
8	7.5	15	12.99	4	51.96
9	8.5	15	12.36	4	49.43
10	9.5	15	11.61	4	46.43
11	10.5	15	10.71	4	42.85
12	11.5	15	9.63	4	38.52
13	12.5	15	8.29	4	33.17
14	13.5	15	6.54	4	26.15
15	14.5	15	3.84	4	15.36
Total length of ribbon anodes required					708.19
5%additional					35.41
Total length after the addition					743.6

Table IV. 24 Distribution bars placement results for R383-B.

N	Spacing $X(m)$	Radius $R(m)$	Length $Y(m)$	Quadrant	Total (m)
1	1.5	15	14.92	4	59.7
2	4.5	15	14.31	4	57.24
3	7.5	15	12.99	4	51.96
4	10.5	15	10.71	4	42.85
5	13.5	15	6.54	4	26.15
Total length of distribution bars required					211.75
5%additional					10.59
Total length after the addition					222.33

Table IV. 25 Number of connection cables needed for the external CP system.

Section	(mm^2)	**16**	**35**	**50**
Quantity $\times 100m$	**R 380-B** **R381-B**	10	2	2
	R 383-B	16	2	2

Table IV. 26 Number of connection cables needed for the internal CP system.

Section	(mm^2)	**16**	**35**	**50**
Quantity $\times 100m$	**R 380-B** **R381-B**	12	2	2
	R 383-B	12	2	2

Table IV. 27 Input variables for the external cathodic protection system SIMULINK program.

	Symbol	**Value**		**Unit**
		R380-B &R381-B	**R383-B**	
Radius of the tank	r	7.5	15	m
Total length of the anodes	Lt	197.18	743.595	m
Number of anodes	N	15	30	/
Total length of the distribution bars	$Ltbars$	71.81	222.332	m
Number of distribution bars	$Nbars$	5	10	/
Cables resistance	$Cres$	0.1155	0.11119	Ω
Current density for 30 degrees	$i0$	0.02		A/m^2

Operating temperature	T	55	℃
Current output of the anode	Is	0,042	A/m
Elctro motive force	FCE	2	V
Soil resistivity	p	130	$\Omega.m$
Width of the anode	l	0.00635	m
Linear resistance of distribution bars	Rcl	0.043	Ω/m
Anode's angle of protection	Q	60	°
Distance between the CP system and the bottom of the tank	d	0.5	m

Table IV. 28 Input variables for the attenuation system SIMULINK program.

	Symbol	**Value**		**Unit**
		R380-B &R381-B	**R383-B**	
Number of anodes	N	15	30	
Ribbon anode resistivity	Z	0.427		$\mu\ \Omega.m$
Length of anode between 2 distribution bars	L	3		m
Anode surface	A	0.000004		m^2
Current output of ribbon anodes	Ia	0,042		A/m
Spacing between 2 anodes	X	1		m
Minimal Distance between the grid and the structure	$r2$	0.5		m
Maximal Distance between the grid and the structure	$r2$	0.707		m
Anode's angle of protection	Q	60		°
Distance between the CP system and the bottom of the tank	d	0.5		m
Resistivity of the soil	p	130		$\Omega.m$

Table IV. 29 Input variables for the internal system SIMULINK program.

	Symbol	**Value**		**Unit**
		R380-B &R381-B	**R383-B**	
Radius of the tank	r	7.5	15	m
Diameter of the tank	D	15	30	m
Wetted height	H	12.86	12.584	m^2
Length of a single anode wire	$Lchapelet$	10.283413	7.4308271	m
Current density for 30 degrees	$i0$	0.002		A/m^2
Operating temperature	T	55		℃
Current output of the anode	Ig	1		A/m
diameter of the anode	l	0.003		m
Number of anodes	N	6		/
Cables resistance	$Cres$	0.11358		Ω
Correction factor for the number of anodes	fc	0.11		/
Deterioration factor	$fdet$	1.0		/
Water resistivity	c	0.2		$\Omega.m$

IV.3.1.6 MATLAB programs

IV.3.1.6.a External program

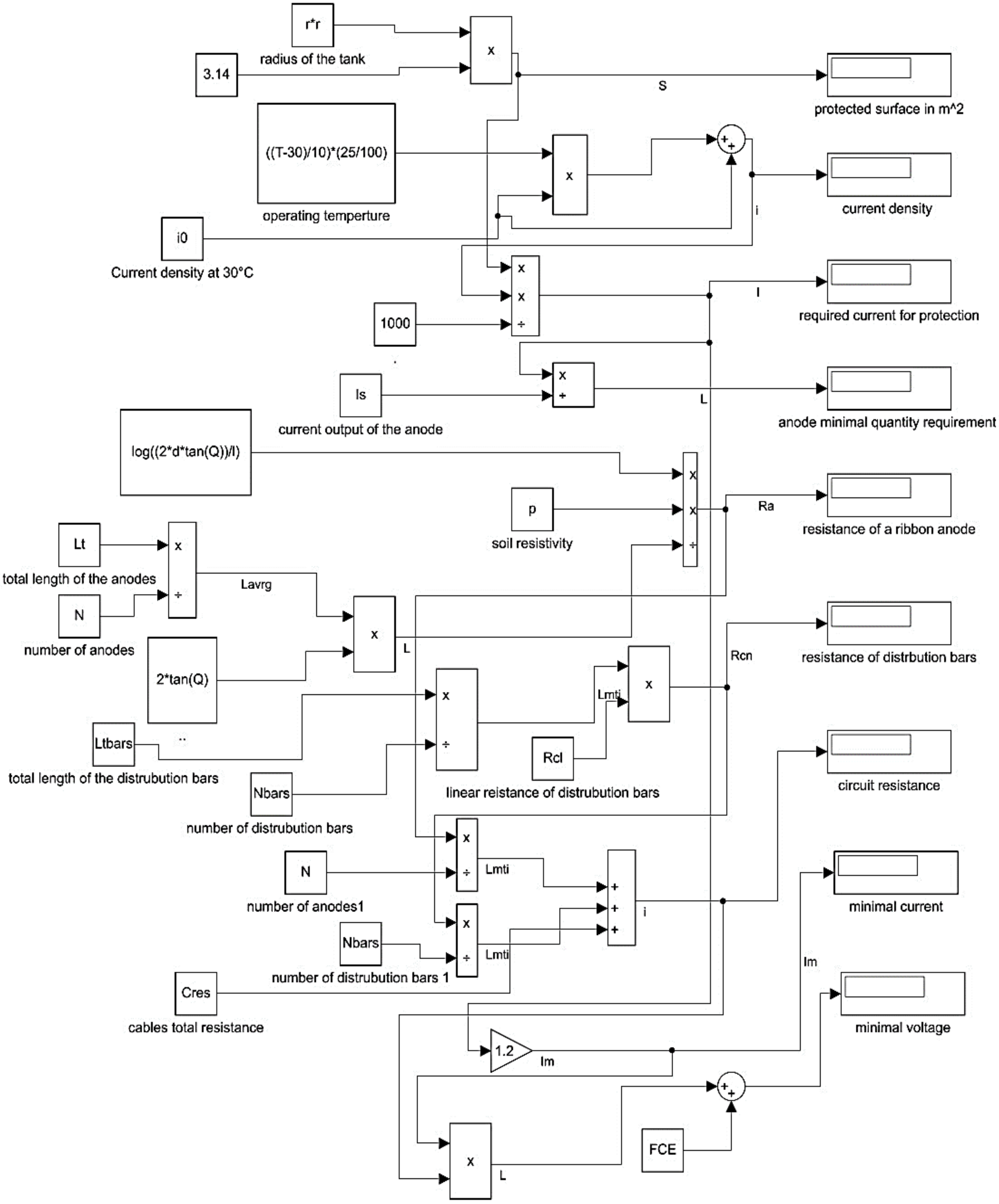

Figure IV. 11 External protection system calculator SIMULINK program.

IV.3.1.6.b Attenuation of external CP program

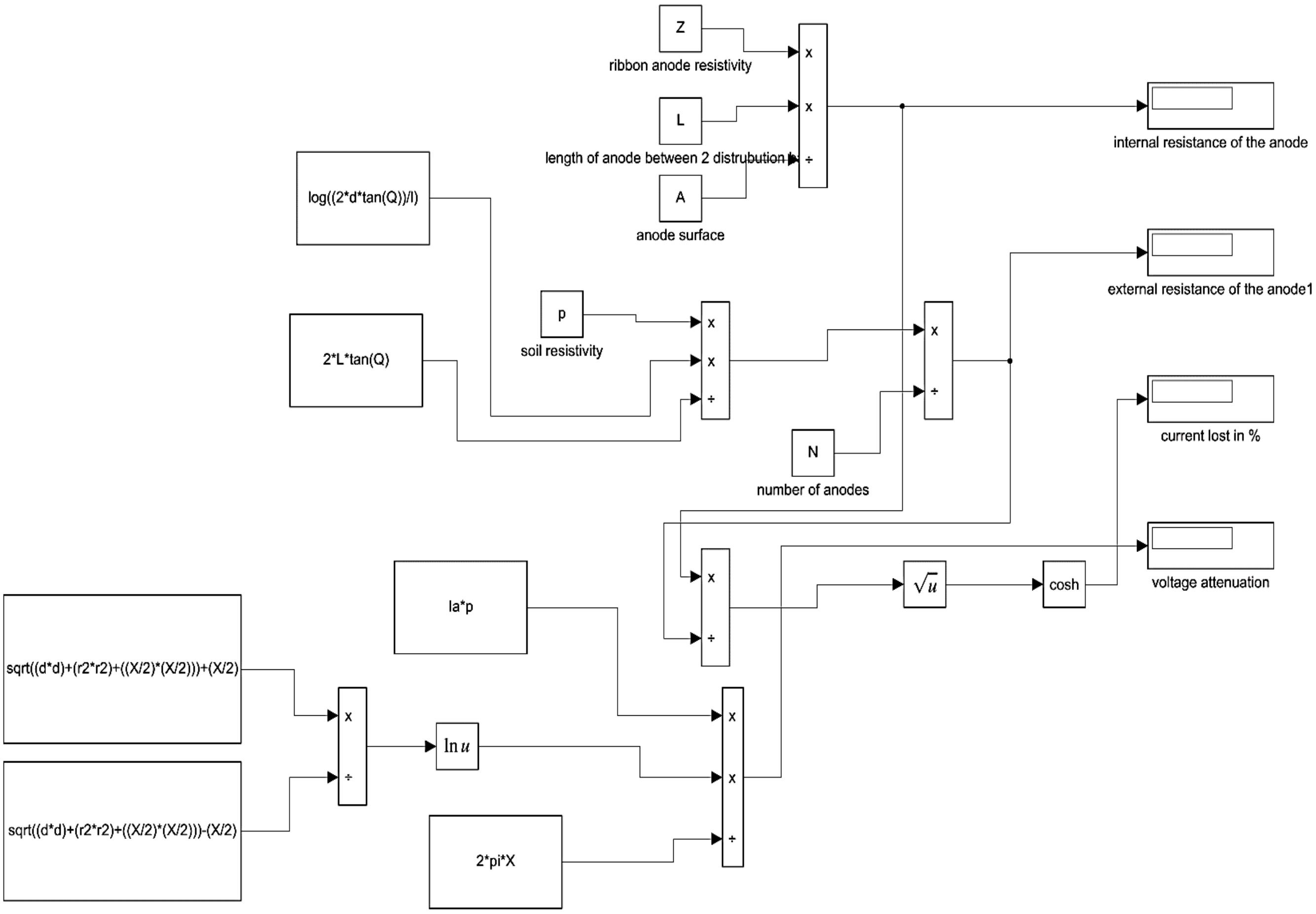

Figure IV. 12 External protection attenuation SIMULINK program.

IV.3.1.6.c. Internal program

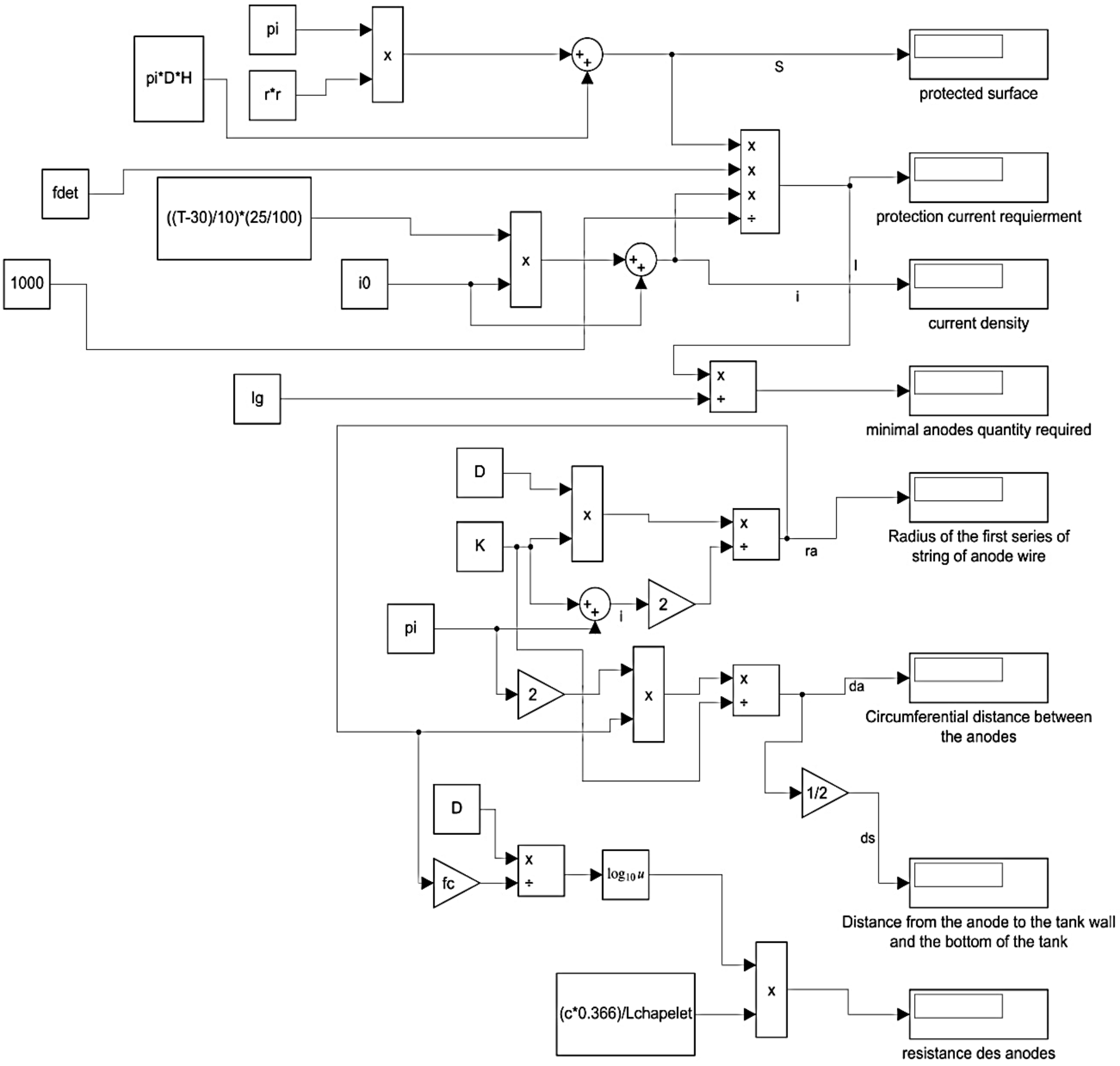

Figure IV. 13 Internal protection system calculator SIMULINK program.

IV.3.1.7 Results and discussion

Table IV. 30 Results of external protection.

Results	R 380-B& R381-B	R 383-B	Unit
Protected surface	176.6	706.5	m^2
Current requirement density	0.0325	0 .0325	A/m^2
Current requierment	5.74	22.96	A
Anodes minimal quantity requirement	136.67	546.696	m
Spacing between the anodes	1	1	m
Spacing between distribution bars	3	3	m

Table IV. 31 The rest of the results for the external protection.

Tanks / Results	R 380-B & R381-B	R 383-B	Unit
Number of anodes	15	30	/
Average length of ribbon anodes	13.15	24.79	m
Resistance of ribbon anodes	15.95	7.72	Ω
Total resistance of ribbon anodes	1.06	0.26	Ω
Number of distribution bars	5	10	/
Average length of distribution bars	14.21	22.23	m
Resistance of distribution bars	0.61	0.96	Ω
Total resistance of distribution bars	0.12	0.096	Ω
Total resistance of cables	0.12	0.11	Ω
Total resistance of the circuit	1.29	0.46	Ω
Minimal current	6.89	27.55	A
Minimal voltage	10.33	14.78	V
Minimal current +30%	8.95	35.82	A

Table IV. 32 Characteristics of the T/R used based on the previous results.

Tanks / Results	R 380-B & R381-B	R 383-B	Unit
Current	10	50	A
Voltage	15	25	V

Table IV. 33 Current attenuation of ribbon anodes.

Tanks Results	R 380-B & R381-B	R 383-B	Unit
Length of an anode between 2 distribution bars	3	3	(m)
Ribbon anode resistivity	0.427×10^{-6}	0.427×10^{-6}	$\Omega.m$
Ribbon anodes surface (width×hickness)	4.0323×10^{-6}	4.0323×10^{-6}	m^2
Internal resistance of ribbon anodes	0.32	0.32	Ω
Ram	73.58	73.58	/
External resistance of ribbon anodes	4.55	2.45	Ω
Current attenuation in the ribbon anodes	1.03	1.07	%

As we see in Table IV. 34, the attenuation of current doesn't exceed 8%, that means is the proper and normal attenuation.

Table IV. 35 Voltage attenuation of ribbon anodes.

Tanks Results	R 380-B & R381-B	R 383-B	Unit
r_{min}	0.5	0.5	m
r_{max}	0.707	0.707	m
Voltage attenuation with rmin	1.144	1.144	V
Voltage attenuation with rmax	0.95	0.95	V

As we see in Table IV. 34, the voltage attenuation is between 0.95V and 1.15V, which means that the structure is receiving adequate amount of protection and the criteria of cathodic protection is achieved.

Table IV. 36 Lifespan of ribbon anodes.

Tanks Results	R380-B & R381-B	R383-B	Unit
Total Surface of the anodes	1.16	9.44	m^2
Current density of the anode	4.96	2.43	A
$\log(t) < 3.3 - \log(i'_a)$	1.48 < 2.6	1.48 < 2.91	$years$
Life span	>>30	>>30	$years$

As we see in Table IV. 35, the life span is more than 30 years which fits the life span expectancy of the project.

Table IV. 37 Results of the internal protection.

Tanks Results	R 380-B & R381-B	R 383-B	Unit
Protected surface	782.33	1891.91	m^2
Current requirement density	0.00325	0.00325	A/m^2
Current requierment	2.54	6.14	A
Anodes minimal quantity requirement	2.54257575	6.1487166	m

For the number of anodes, we found at the beginning two anodes, and that will not do the job as we see below, because the protection current is not even reaching the walls.

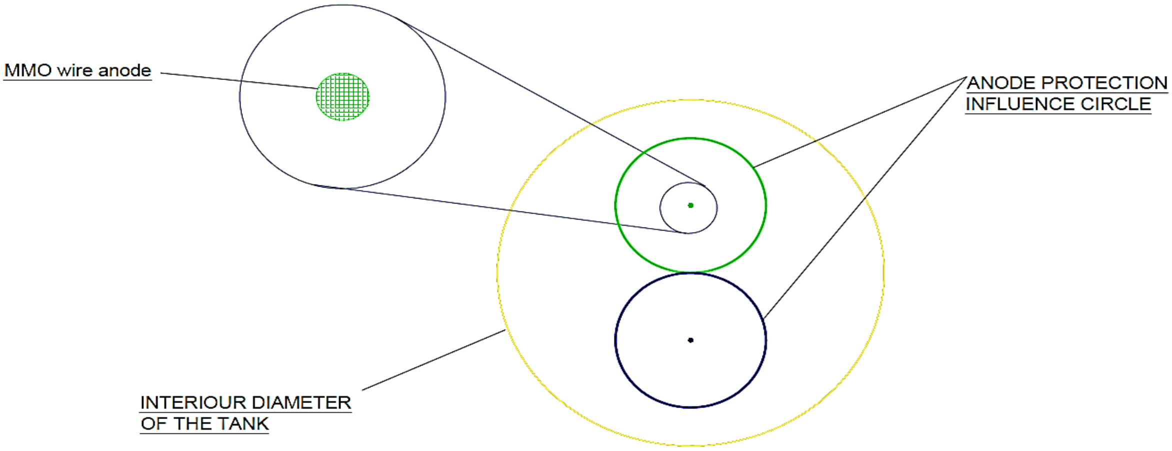

Figure IV. 14 Internal protection influence of two anodes on the tank wall.

Then we add two more anodes and the desired protection is not fulfilled yet, there is spaces that are not protected as we see below:

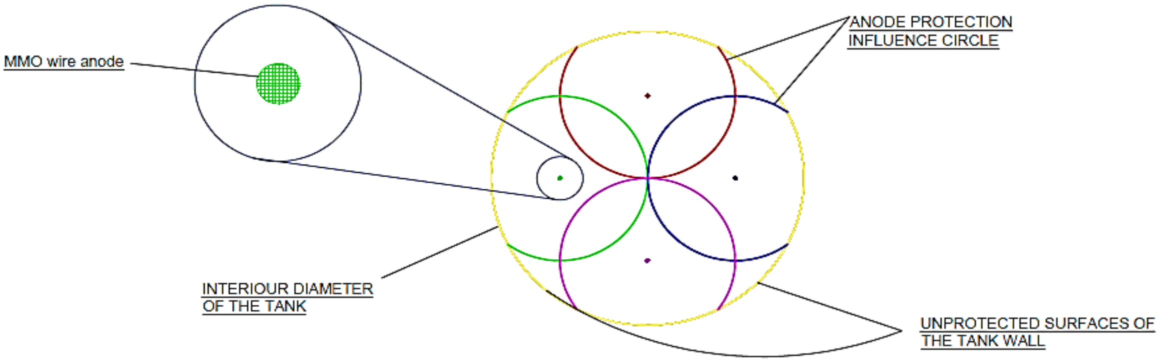

Figure IV. 15 Internal protection influence of four anodes on the tank wall.

Finally we add two more anodes and we get the results shown in below, which indicate that the walls and the bottom surface of tanks are completely protected.

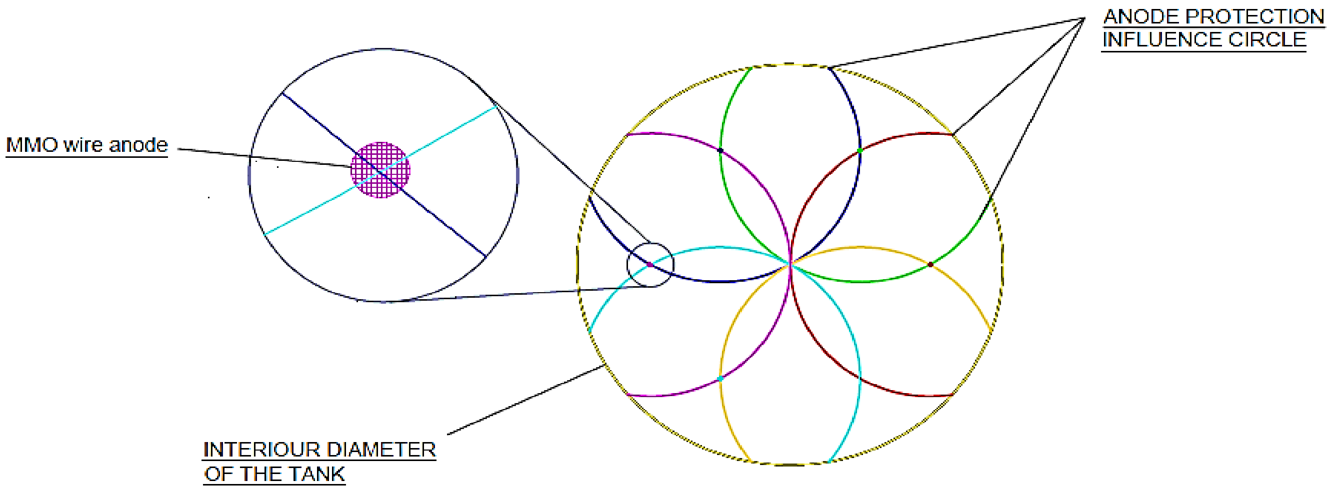

Figure IV. 16 Internal protection influence of 6 anodes on the tank wall.

Table IV. 38 Wire anodes placement and resistance results

Tanks **Results**	**R380-B & R381-B**	**R 383-B**	**Unit**
Radius of the first series of string of anode wire	4.92	9.85	m^2
Circumferential distance between the anodes	5.15	10.31	mA/m^2
Distance from the anode to the tank wall and the bottom of the tank	2.58	5.15	m
Length of a single anode wire	10.28	7.43	m
Correction factor	0.54	1.08	/
Anodes resistance	0.01	0.014	Ω
Resistance of the cables	0.1135	0.1135	Ω
Resistance of anodes material	0.47	0.34	Ω
Total resistance of the circuit	0.595	0.468	Ω
Minimal current	3.05	7.37	A
Minimal voltage	3.81	5.45	V

Table IV. 39 Characteristics of T/R.

T/R specifications	**R 380-B & R381-B**	**R 383-B**	**Unit**
Current	10	15	A
Voltage	10	15	V

IV.3.1.8 Schematic diagrams

IV.3.1.8.a External cathodic protection system for R380-B and R381-B tanks

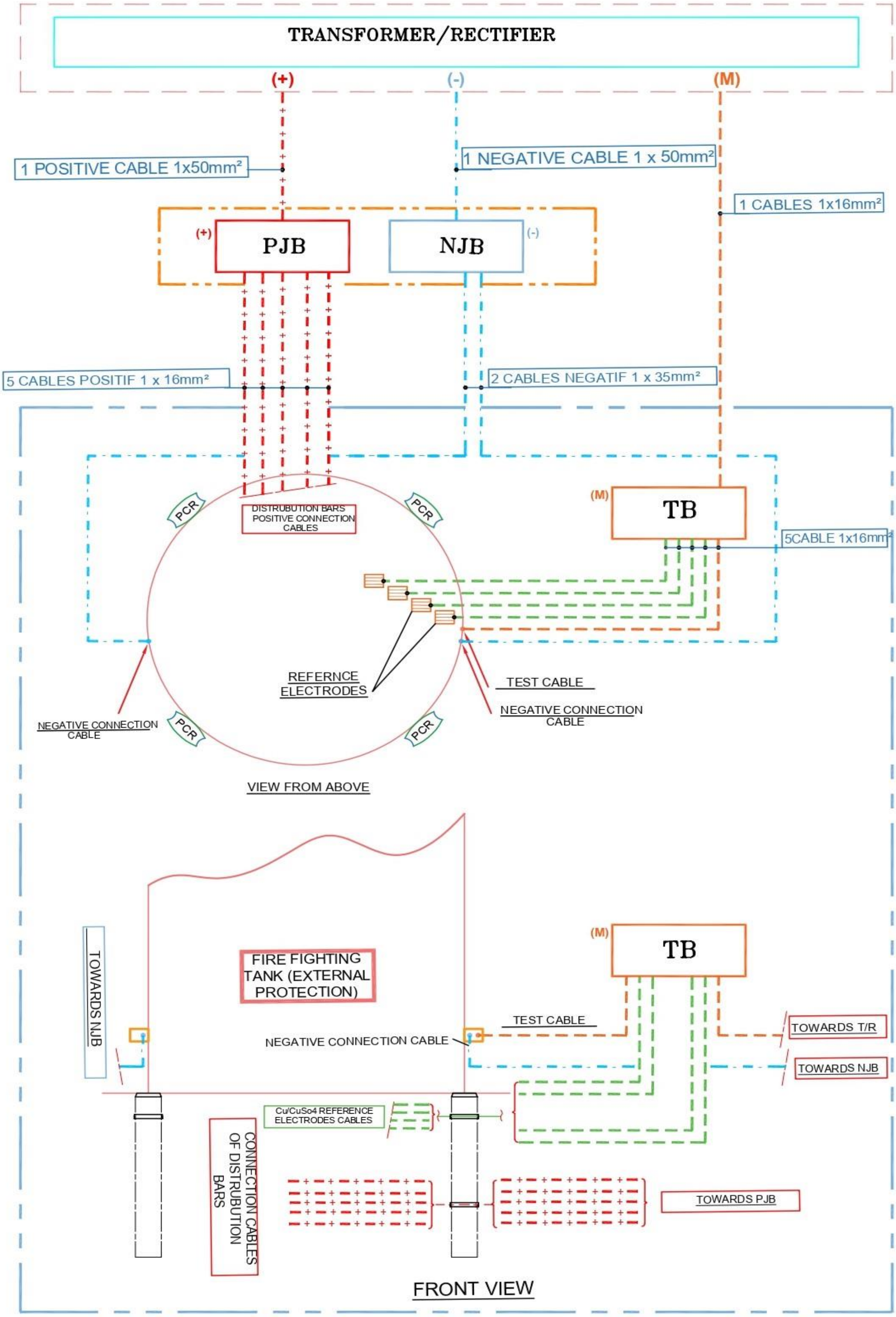

Figure IV. 17 Schematic diagram of the external CP system for R380-B & R381-B tanks.

IV.3.1.8.b External cathodic protection system for R383-B tank

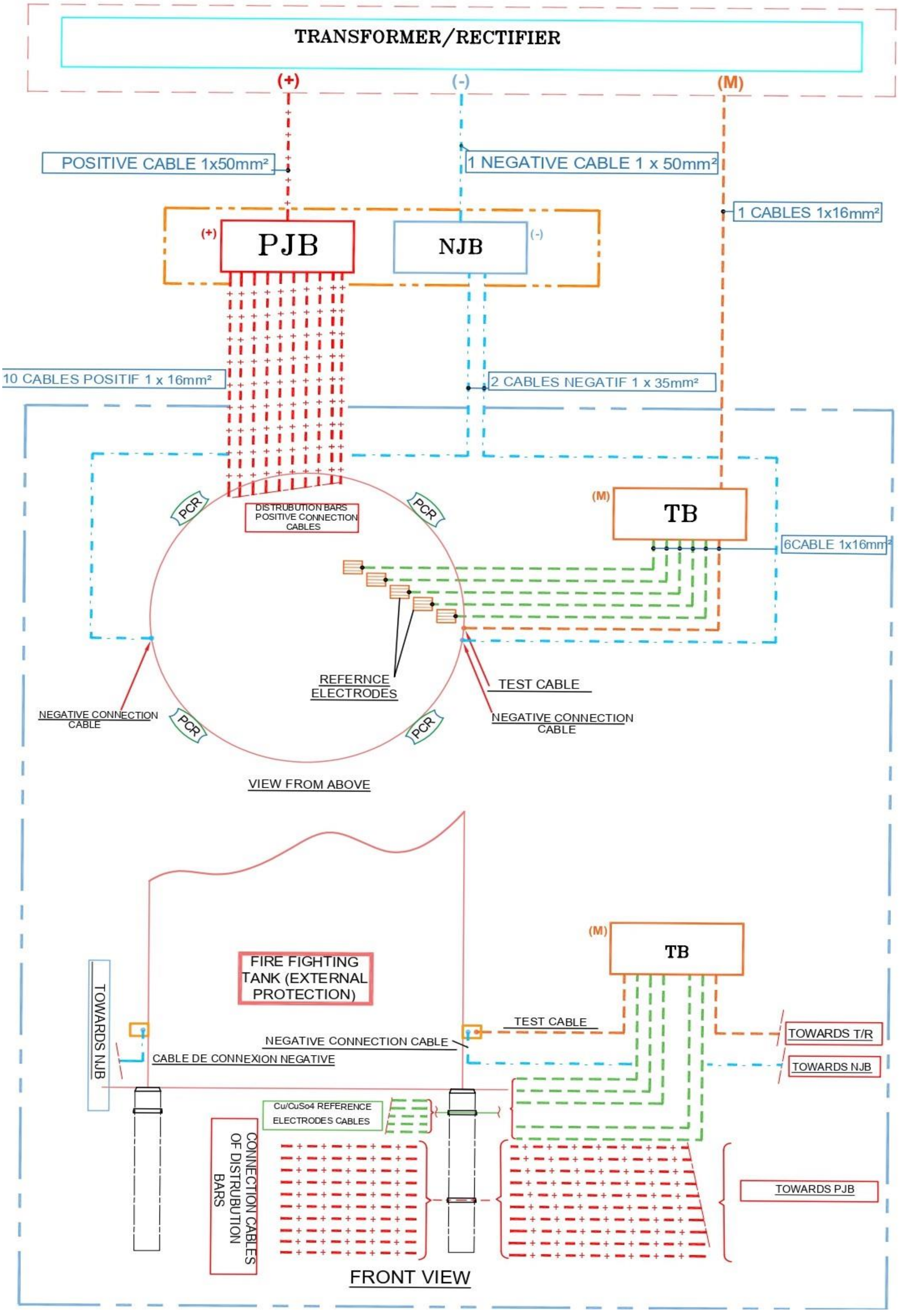

Figure IV. 18 Schematic diagram for the external CP system for R383-B.

IV.3.1.8.c Internal cathodic protection system for the three tanks

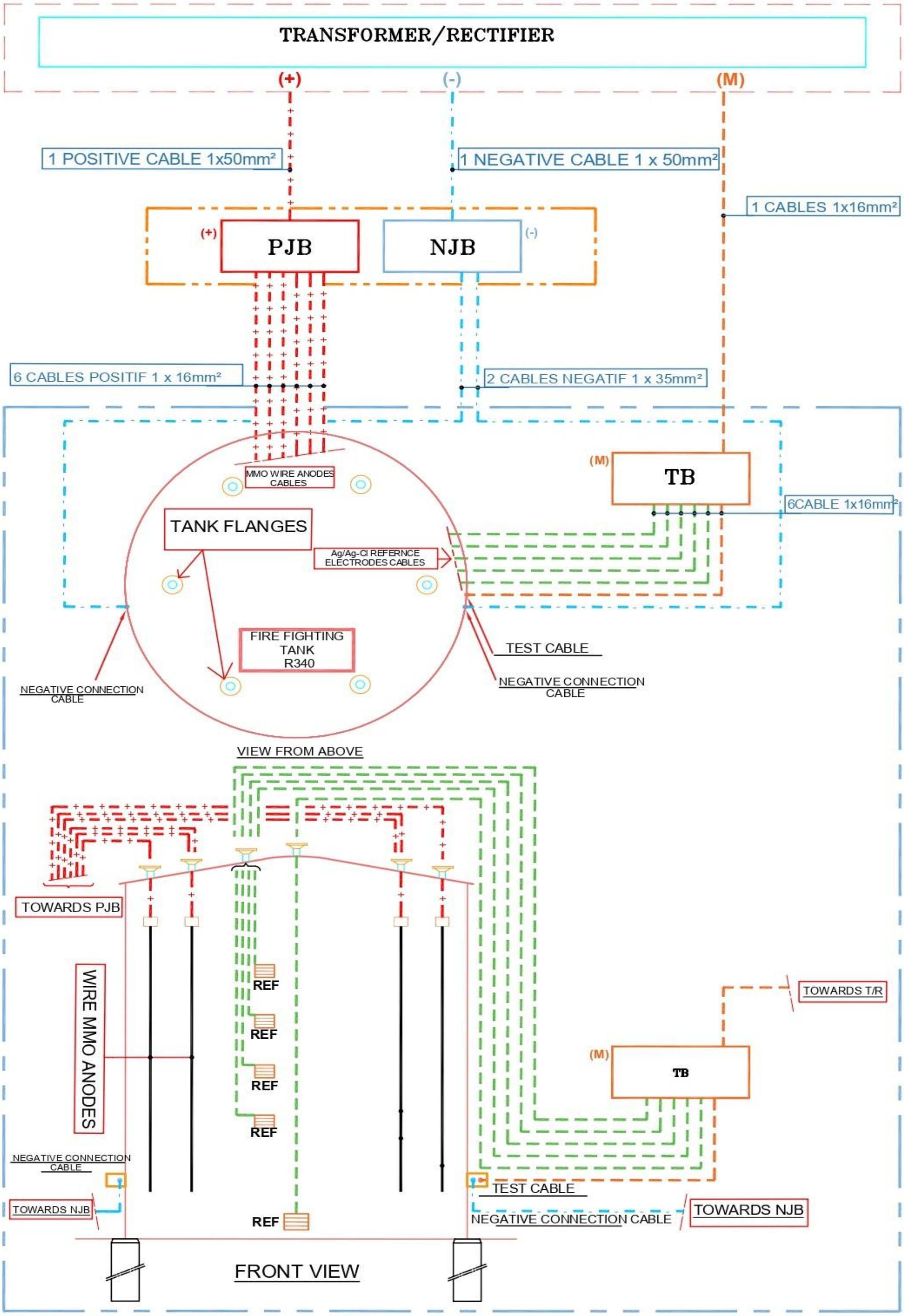

Figure IV. 19 Schematic diagram for the internal CP system of the the three tanks.

IV.3.2 Realization of the external cathodic protection system

The initial stage of realization involves preparing the site and drilling the proper hole for the tank. Next, the HDPE membrane is implanted at a depth of 0.6 meters relative to the tank bottom.

The grid system is installed at a depth of 0.5 meters in reference to the bottom of the tank. We add a 0.3 meter layer of sand, then we place the permanent reference electrodes and the PVC tube for monitoring. Then we add the final layer of sand.

IV.3.2.1 T/R installation

The transformer rectifier is fed by an external source of alternating current. The DC output of the TR is adjustable to meet the varying current demands of the cathodic protection current requirements throughout the life of the system.

Installation tests shall be performed to ensure the right functioning of the T/R. The tests should include at a minimum:

- Verification of proper installation of oil, silica gel, etc.
- Power up and no load test for one hour
- Testing at 50% capacity for two hours with a fictive load connected to the T/R’s continuous circuit.
- 100% load test for two hours with a fictive load connected to the T/R's DC circuit
- Powering down and connecting the DC cables to the appropriate terminals.
- Checking the AC power and ground connections Calibration of the unit's counters.

All T/R operation tests must be performed with the secondary (DC) cables disconnected from the structure to be protected. If an electronic component of the T/R must be replaced during the installation tests, due to rectifier malfunction or unit failure to meet performance requirements, then the test must be repeated.

The T/R must be installed outside the hazardous area, outside the bundwall.

IV.3.2.2 Ribbon anodes and distribution bars installation

The impressed current cathodic protection system (ICCP) is of the "HARCO" type. It consists of a grid under the tank with MMO (mixed metal oxides) ribbon anodes and titanium distribution bars, installed perpendicularly to the ribbon anodes. This grid system allows a uniform distribution of the protection current and the redundancy of the electrical connections increases the reliability of the cathodic protection system.

We measure 0.5 meter from any side of the bottom circle and we place our first anode depending on the length of the anode, then we measure 1 meter and place the second anode, and so on until we reach the other side of the circle.

At each intersection of a ribbon anode with a distribution bar at least two welds per point are made to ensure good electrical continuity.

The two metals are placed one on top of the other, then strongly maintained under pressure by the welding machine, between two electrodes, before a strong current passes through them allowing, after a brief pause, in order to cool the melting point, the release of the two metals united forever by welding.

There is no filler metal for this welding method, it is carried out under pressure with a strong electric current as heating

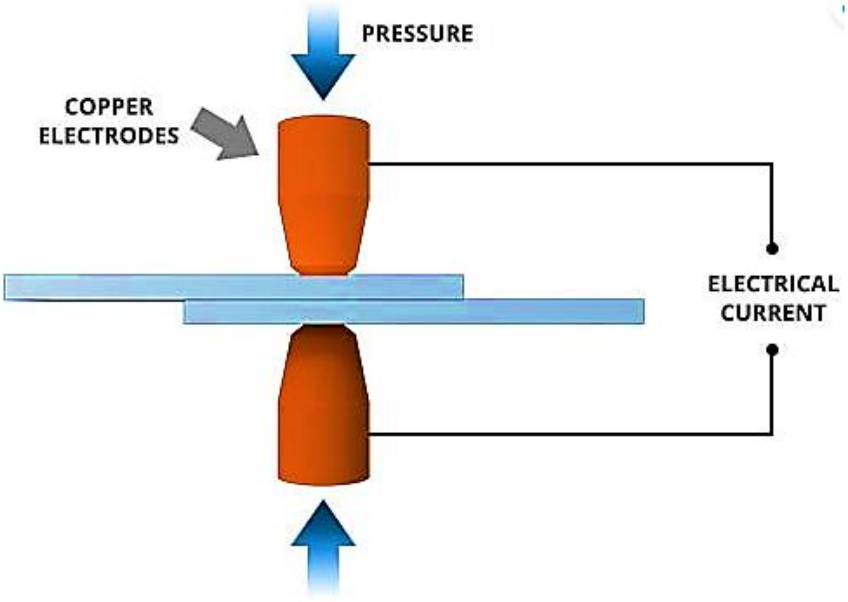

Figure IV. 20 The working mechanism of spot welding.

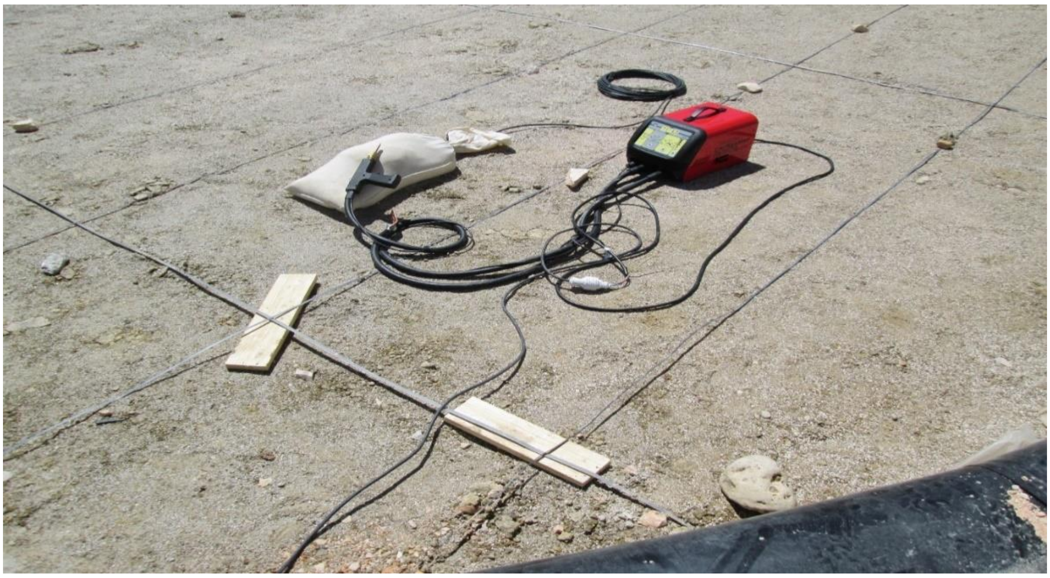

Figure IV. 21 Spot welder.

Figure IV. 22 Placement of ribbon anodes on top of the distribution bars.

Figure IV. 23 Rolls of ribbon anodes and distribution bars.

IV.3.2.3 Polarization cell

Each impressed current catholically protected storage tank is connected to ground. Each connection to the grounding system must be made via polarization cells in order to limit the interference between the cathodic protection system and other systems.

Four polarization cells will be placed diametrically opposed for each of the three tanks.

IV.3.2.4 Installation of NJB, PJB and TB

Once the foundations of the NJB, PJB and TB are completed, the installation is done as follows:

- Check that the NJB, PJB and TB are not damaged externally and internally (mechanically and electrically).
- Install the NJB, PJB and TB and secure it to its bracket.
- Check for proper attachment/hooking.
- Connect the grounding cable.
- Connect the cables to the different circuits/structures.

- Check the connection to the grounding circuit.
- Check that the cable glands are appropriate for the cable cross-section and properly tightened.
- Check that the spare cable glands are equipped with suitable plugs.
- Check that the cables are correctly tightened and fixed in the NJB, PJB and TB.
- Check the setting of the variable resistors.

Positive and negative junction boxes are installed outside the bundwall. Unlike the test box, which should be installed near the tank and must therefore be suitable for installation in hazardous areas.

IV.3.2.5 PVC tube

In order to allow control recordings of the system, a PVC tube with an internal diameter of 75 mm, is installed under the tank at the same depth as the permanent reference electrodes (150-200 mm minimum).

This tube passes through the center of the tank and its length must be sufficient to also pass through the concrete ring supporting the tank. Inside this tube a polypropylene cord will be installed so that a portable reference electrode can be slid inside the tube, to take potential measurements along the diameter of the tank.

Figure IV. 24 Monitoring tube underneath the tank’s bottom surface.

IV.3.2.6 Installation of reference electrodes

The possible regulation of the cathodic protection system will be carried out by permanent copper/copper sulfate (Cu/CuSO4) reference electrodes which are installed under the storage tank, at a minimum depth of 150-200 mm from the surface of the tank and at mid-distance between two ribbon anodes.

IV.3.3 CP external systems equipment implantation plans

IV.3.3.1 External cathodic protection system for R380-B and R381-B tanks

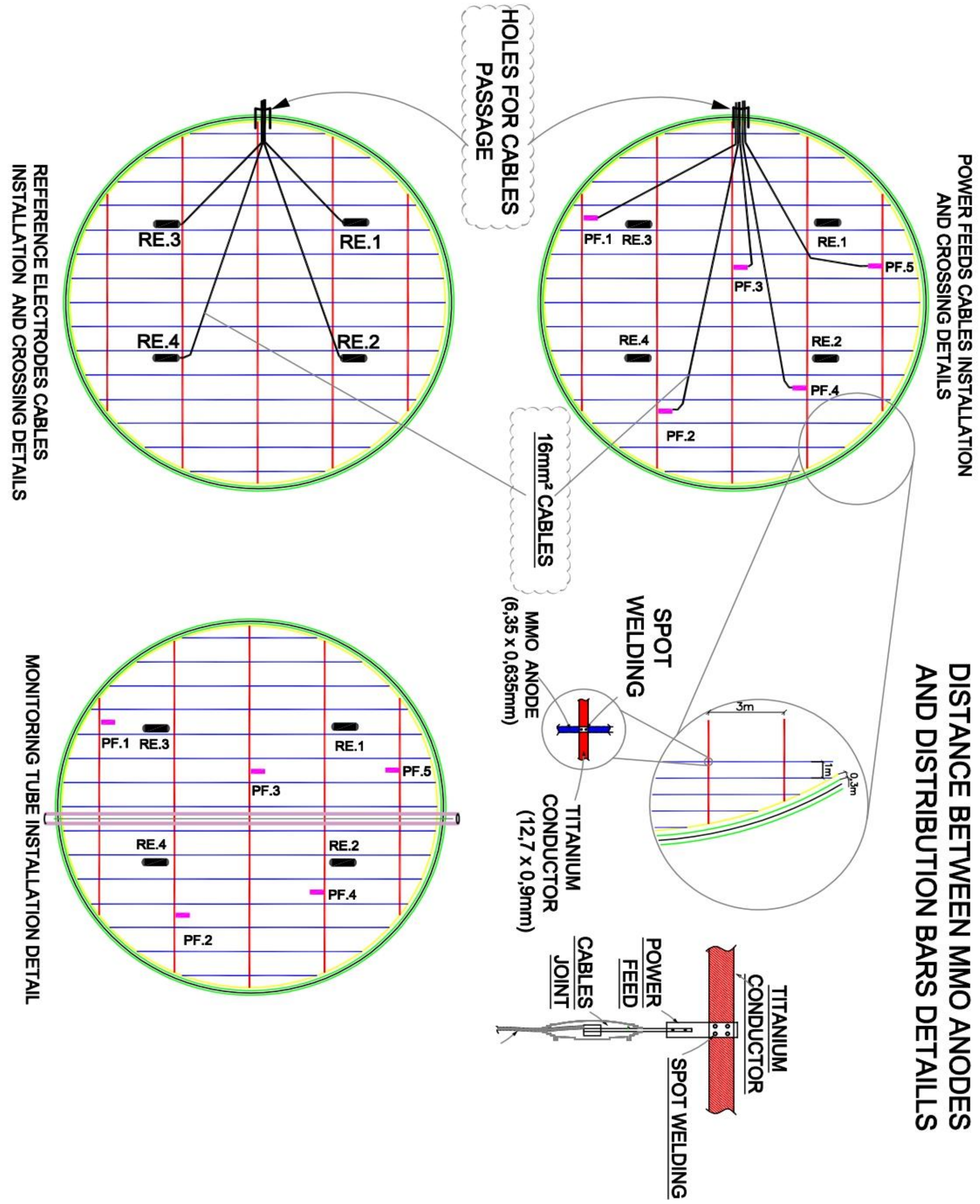

Figure IV. 25 Implantation plan of the external CP system for R380-B & R381-B.

IV.3.3.2 External cathodic protection system for R383-B

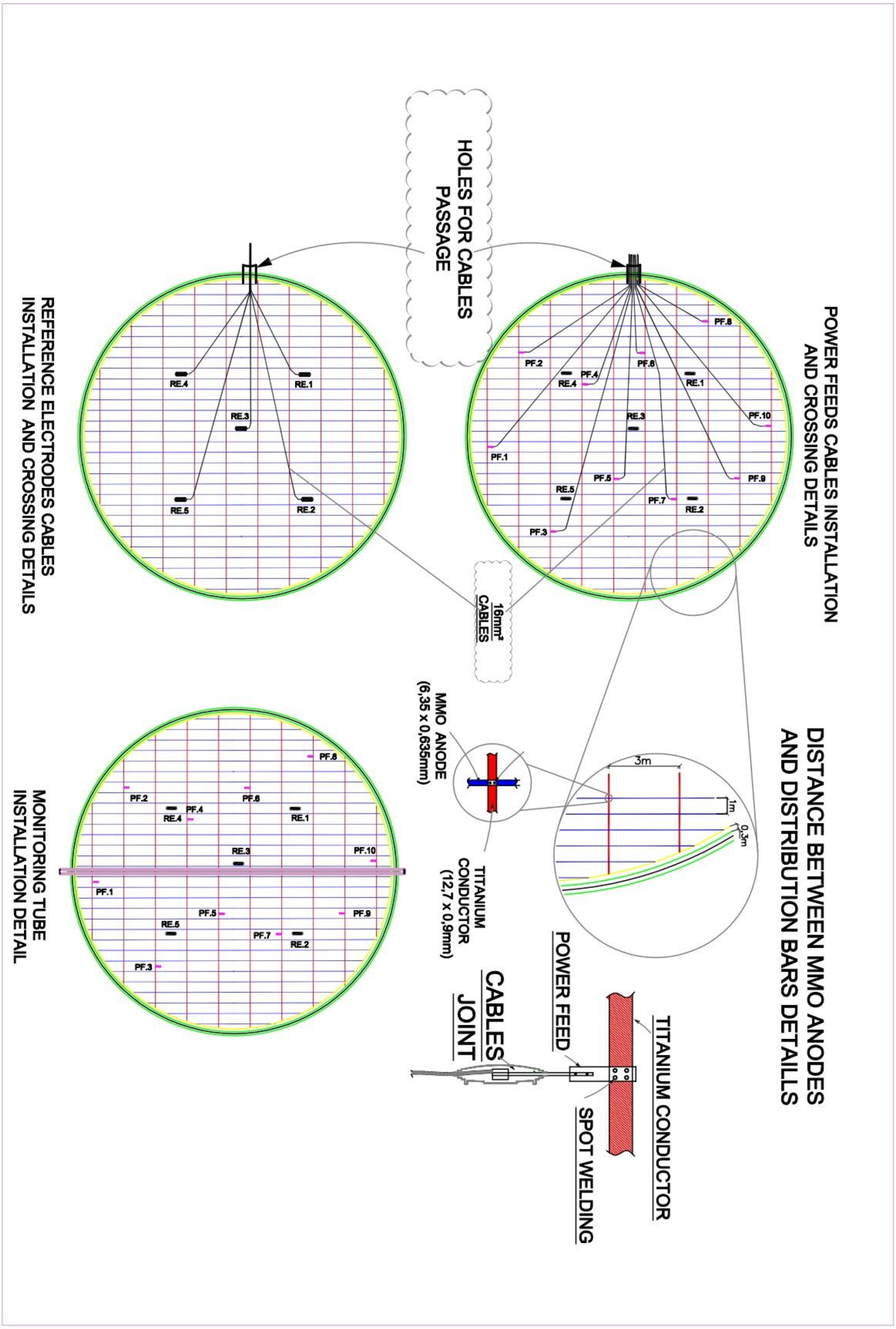

Figure IV. 26 Implantation plan of the external CP system for R383-B.

IV.3.4 Internal CP system realization

IV.3.4.1 Anodes

The impressed current anodes can be positioned as follows:

a. First of all we will remove the plastic bag protecting the anodes.
b. Then, Check if the anodes and cables are not damaged.
c. We are going to unwind the polymer rope and fix it at the plate located in the bottom surface of the tank, and in the plate located at the top of the tank, to lower the anodes into the tank.
d. Unwind the anode cable and check that it is not damaged.
e. Lower the anode using the rope until it reaches the distance calculated previously and then fix the anode with the robe with plastic fixing strip. In no case should the anodes be suspended by the power cable.
f. Keep the anode in a vertical position and wind up the remaining length of cable to prevent damage to the cable insulation before connecting it to the junction box.
g. Repeat the same steps for each anode to be installed in the tanks.
h. Then we are going to gather anodes cables, each 3 or 4 anodes cables will be gathered and taken out through the tank flange to the negative junction box outside the tank.

IV.3.4.2 Reference electrodes

The monitoring of the internal CP system will be carried out by five silver silver chloride reference electrode (Ag/AgCl).

After we divide the height of the tank on four levels, we will place a reference electrode in each level near the tank walls.

The fifth reference electrode will be placed in the middle of the tank near the bottom.

The cables of the reference electrode will be gathered and taken out in one tank flange to the test box outside the tank.

IV.3.5 CP external systems equipment implantation plans

IV.3.5.1 Internal cathodic protection system for R380-B R380-B and R381-B

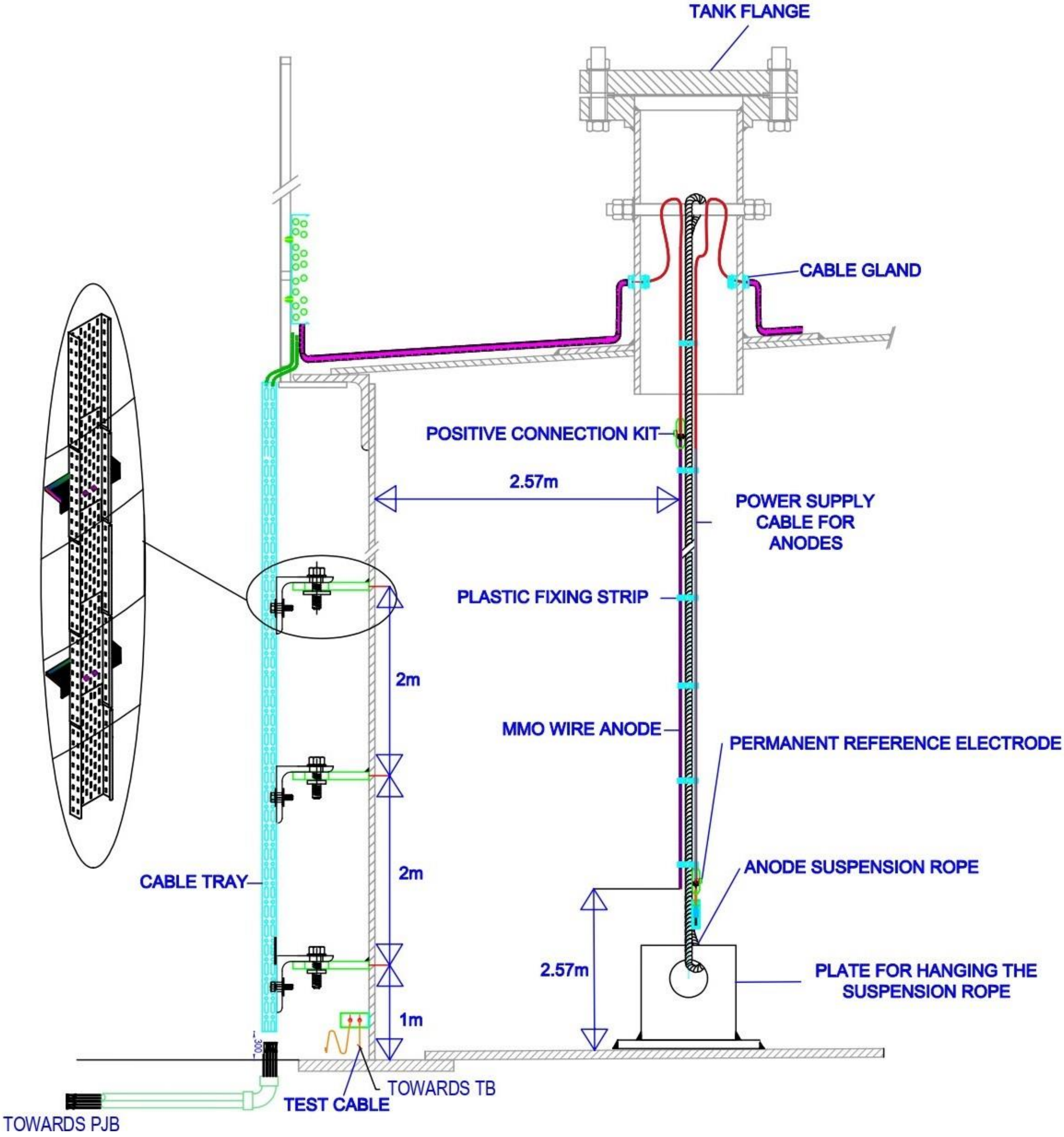

Figure IV. 27 Implantation plan of the internal CP system for R380-B & R381-B tanks.

IV.3.5.2 Internal cathodic protection system for R383-B

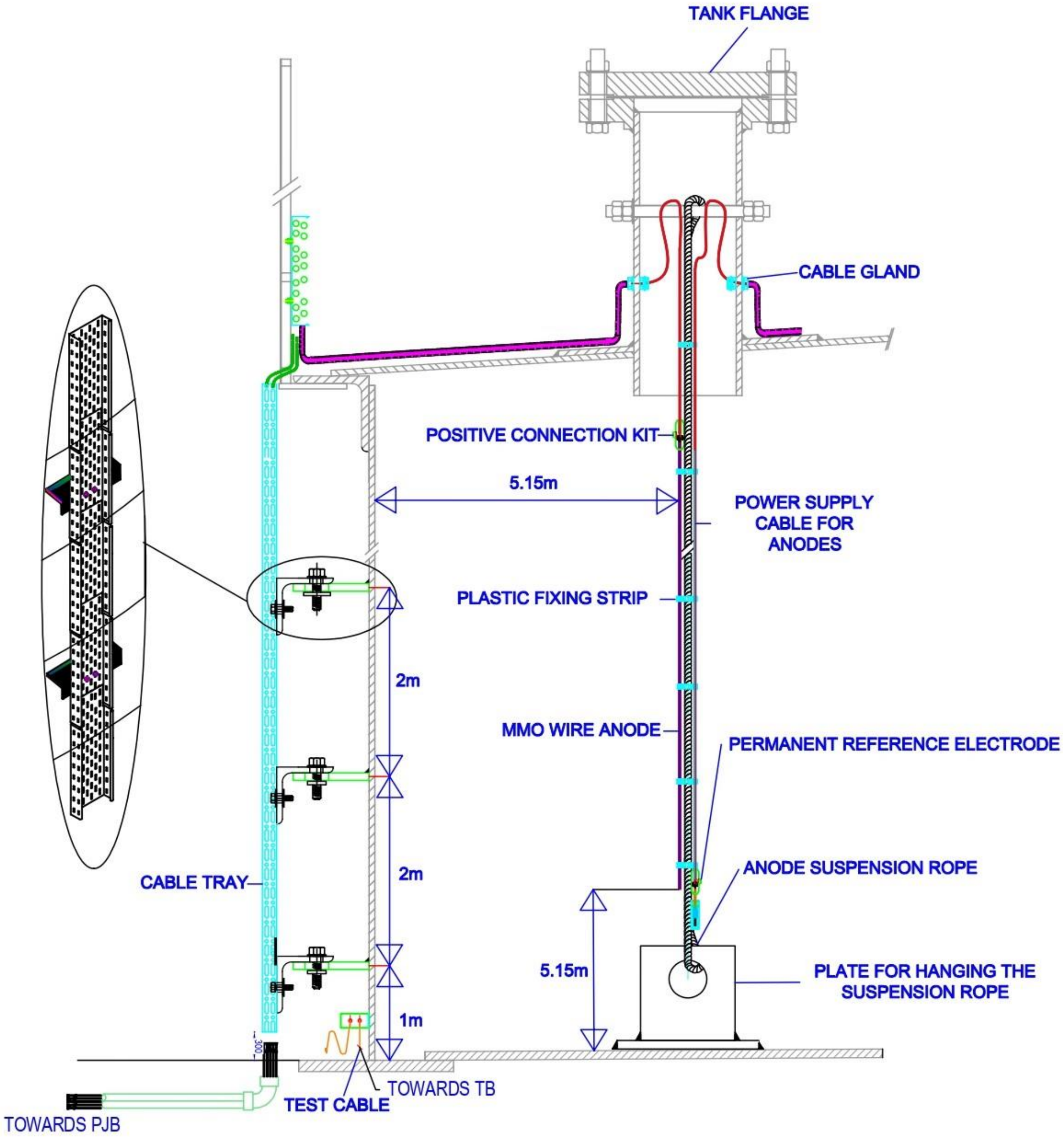

Figure IV. 28 Implantation plan of the external CP system for R380-B & R381-B.

IV.4 Conclusion

In this chapter, we presented the ENGCB project of realization three firefighting water tanks in the compression center Kenenada-Relizane, with 30 years life expectancy.

We have showed the design procedure of the internal and external cathodic protection systems, and we created SIMULINK schemes that have been used to determine all of the characteristics of the systems, such as: current requirement, number and positioning of anodes, circuit resistance, minimal current require, minimal voltage required,etc. With the last results, we were able to choose suitable transformer/rectifier that can provide adequate protection current for each tank.

Based on the SIMULINK schemes results, we explained the cathodic protection realization procedure and we were able to draw schematic and implantation plans in AUTOCAD.

So In the aim of achieving the 30 years life span, corrosion prevention methods are used. For the internal surfaces, coating is applied but it cannot stop corrosion completely. Inhibition is not used, because the hazards it poses on the environment in case the water gets leaked out. Impressed current cathodic protection method is used instead of sacrificial anodes cathodic protection method, because the long life span of the first method, and the enormous weight applied on the roof of the tank in the second method, which is not practical.

For the external bottom surfaces, coating cannot be used, because it needs periodic inspection and maintenance but in our case, it is not accessible. Inhibition is not used due to the hazards it poses on the environment. Impressed current cathodic protection method is used instead of sacrificial anodes method because the long life span of the first method and the high consumption rate of the second method anodes, so they have to be replaced regularly which is impossible in our case , because the cathodic protection system is directly underneath the tank and it cannot be reached.

General conclusion

General conclusion

This project is a study and design of internal and external cathodic protection systems for fire-fighting water tanks located in the compression center of Kennanda-Relizane.

The tanks are made out of steel which can be corroded when exposed to soil or water, so we have to use passive and active to mitigate corrosion. Inhibition can cause serious hazards on the environment, so it’s not used. Coating is applied on the internal surfaces, but not on the external bottom surface, because it can’t be reached for maintenance and monitoring. So cathodic protection systems are used.

In this project, we have used the impressed current method over the sacrificial anode method for three reasons:

- The sacrificial anode method cannot last for the life span desired in this project, which is 30 years, this method can’t surpass 10 years if we want to implant an efficient and practical CP system.
- Sacrificial anodes weigh significantly more than impressed current anodes because of the high consumption rate of sacrificial anodes, Because the anodes are suspended from the tank's roof for the inside surfaces, the weight on the roof will be enormous, and the roof may not resist.
- The external protection system is directly underneath the tank, and it can’t be reached, so a long life span protection system should be used, and sacrificial anodes systems can’t provide that.

We have presented the design procedure, which was developed by the NACE organization, and based on the data from the site and the tanks we got from the company responsible for the project, ENGCB. Based on the previous design procedure, we have presented a SIMULINK schemes for the calculation of the CP system characteristics. This model can save time, increase the accuracy of the calculations, and be used for future similar projects. Then we explained the procedure for realization of the cathodic protection systems based on the practical work we did in the company, and we have presented implantation plans of the CP equipment in AUTOCAD.

Finally, cathodic protection is a well-known corrosion prevention method, widely used in different fields, because it proved its efficiency by increasing structures' lifespan, saving costs, ensuring safety, and protecting the environment.

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Appendix

Appendix A

Galvanic series chart of metals and alloys

Least noble (Corroded)	***Magnesium***
↓	***Zinc***
	Aluminum
	Cadmium
	Steel
	Lead
	Tin
	Nickel
	Brass
	Bronze
	Copper
	Stainless steel
	Silver
	Titanium
	Graphite
	Gold
Most noble (Protected)	***Platinum***

Appendix B

Characteristics of sacrificial anodes

Anode type		**Zinc**
composition	**Zn**	The rest
	Mg	0
	Al	0.1-0.5
	In	0
	Pb	0.006
	Si	0.125 max
	Cu	0.005 max
	Fe	0.0014
	Hg	0
	Cd	0.025-0.15
	Mn	0
	Ni	0
	Sn	0
Advantages		- Well-adapted potential for the protection of compact structures in seawater. - Reliable performance in various operating conditions (soil, seawater, mud, confined environments ...). - Not very sensitive to marine fouling
Limitations		- Limited range due to low potential. - Operating temperature limited to 60°C - Higher cost of anode/year than aluminum (Case of offshore structures).
Applications		- Short buried pipes. - Submerged structures. - Metal capacitors (interior and/or exterior).

Anode type		**Aluminum**	
		Mercury aluminum anodes	**Indium aluminum anodes**
Composition	**Zn**	0.3-3	0.5-5
	Mg	0	0-2.2
	Al	The rest	The rest
	In	0	0.005-0.05
	Pb	0	0
	Si	0.1 max	0.1 max
	Cu	0.005 max	0.01 max
	Fe	0.1-0.13 max	0.1-0.13 max
	Hg	0.03-0.05	0.03-0.05
	Cd	0	0
	Mn	0	0
	Ni	0	0
	Sn	0	0
Advantages		- Lower A/year cost due to its high practical ability. - Potential well suited to the protection of structures compact in seawater. - Can be used in tanks - Remain active at high temperatures, unlike zinc alloys, however, a drop in performance is observed of up to 20 to 30% for 80 to 100°C.	
Limitations		- Current common alloys are generally not recommended for poorly renewed environments, therefore not usable in the ground. - Vulnerable to marine fouling, but the practical consequence of these does not seem harmful. - Current common alloys are generally not recommended for the protection of works entirely painted due to the risk of passivation if the anode is weakly stressed.	
Applications		- Offshore platforms. - Hot offshore pipes. - Metallic capacities (interior).	

Anode type		**Magnesium**	
		Standard type	**Hight potential type**
Composition	**Zn**	2-4	0
	Mg	The rest	The rest
	Al	5-7	0.01 max
	In	0	0
	Pb	0	0.01 max
	Si	0.3 max	0.05 max
	Cu	0.1 max	0.02 max
	Fe	0.003 max	0.03 max
	Hg	0	0
	Cd	0	0
	Mn	0.15 min	0.5-1.3
	Ni	0.003 max	0.001 max
	Sn	0	0.01 max
Advanteges		- High range due to its high potential. - Rapid polarization of the structure (precipitation of the deposit calcium-magnesium in seawater). - Low specific weight.	
Limitations		-Electromotive force is sometimes superabundant for protection in salt water (Useless overconsumption, risk of paint blistering). - Low lifespan (replacements required) - Poor performance in seawater corrosion. - Highest Anode per year cost.	
Applications		- Protection of buried pipes on low lengths. - Protection of offshore pipelines over several kilometers from platforms	

Appendix C

Characteristics impressed current anodes

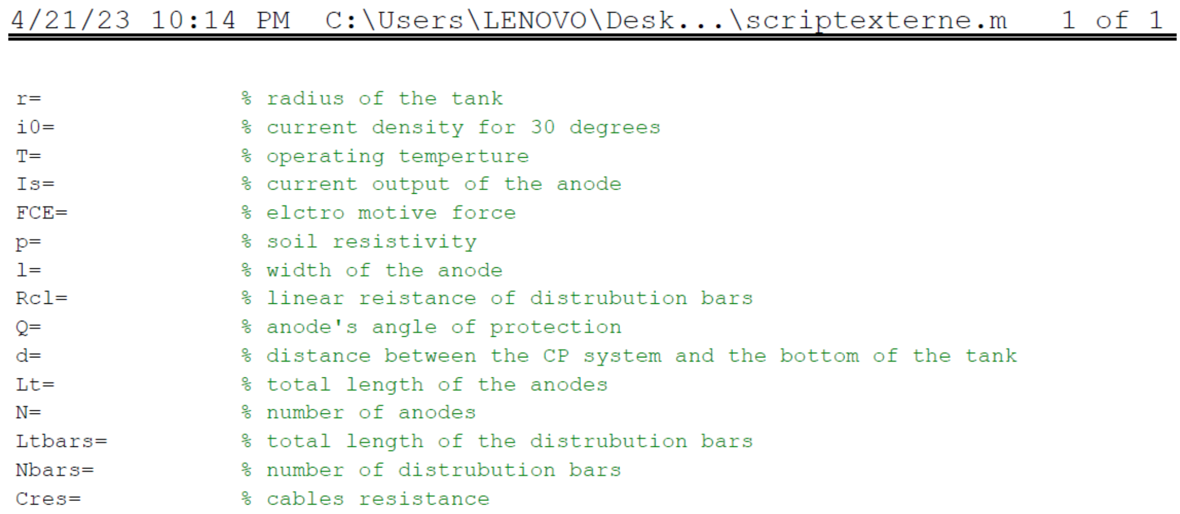
Anodes	**Environment**	**Consumption rate (kg/A.year)**	**Allowable current density A/dm^2**	**Advantages**	**Limitations**
Silicon chromium iron	Suitable for all environments.	0.3	0.2	- Can be installed without backfill. -Acid resistant -efficient under wet conditions.	- Poor performance in sulfates - Size-large and heavy - Expensive - Poor performance under dry conditions
Magnetite	Suitable for all environments.	0.01	1.2	- Efficient. - Can be used in different types of electrolytes.	- They are fragile when exposed to sunlight or high temperature during laying work.
Graphite	Suitable for all environments.	1	0.08	- Readily available. - Efficient under dry conditions. - Economical.	- Large size - Brittle and breaks easily. - Soft and erodes in flowing water. - Oxygen evolution increases consumption
Titanium Platinum	Seawater, brewed fresh water, the internal surface of pipes for drinking use	9	5 to 7	- Performs well with chlorine evolution. - Efficient in seawater. - Variable size and light weight.	- Performs poorly with O2. - Not recommended underground. - Breakdown voltage cannot be exceeded.
Niobium platinum	Seawater and brewed fresh water	9	10		

Tantalum platinium		9	20		- Wear rate increases for deep anodes.
Mixed Metal Oxide	Seawater, mud, and underground	1	10	- Low consumption rate - Resistant to acid attack - Economical cost - High current density rating	- Low breakdown voltage
Conductive polymer			0.13	- Easy installation - Good where a distributed anode is required - Economical.	- Relatively low surface current density limit - Limited to temperatures below about 66o C (150o F). - Susceptible to lightning.

Appendix D

MATLAB script of SIMULINK schemes input variables

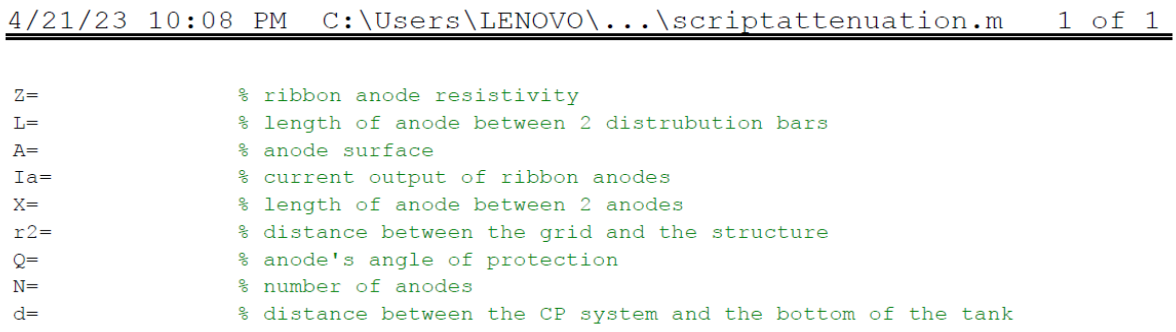
External



```
4/21/23 10:14 PM  C:\Users\LENOVO\Desk...\scriptexterne.m   1 of 1

r=                 % radius of the tank
i0=                % current density for 30 degrees
T=                 % operating temperture
Is=                % current output of the anode
FCE=               % elctro motive force
p=                 % soil resistivity
l=                 % width of the anode
Rcl=               % linear reistance of distrubution bars
Q=                 % anode's angle of protection
d=                 % distance between the CP system and the bottom of the tank
Lt=                % total length of the anodes
N=                 % number of anodes
Ltbars=            % total length of the distrubution bars
Nbars=             % number of distrubution bars
Cres=              % cables resistance
```

External attenuation



```
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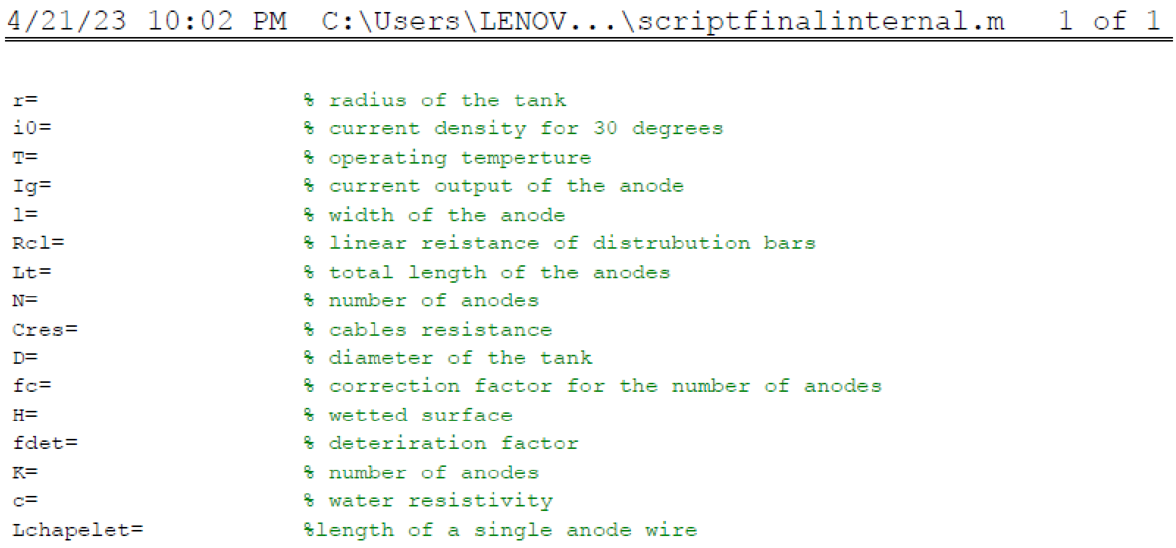
Z=                 % ribbon anode resistivity
L=                 % length of anode between 2 distrubution bars
A=                 % anode surface
Ia=                % current output of ribbon anodes
X=                 % length of anode between 2 anodes
r2=                % distance between the grid and the structure
Q=                 % anode's angle of protection
N=                 % number of anodes
d=                 % distance between the CP system and the bottom of the tank
```

Internal



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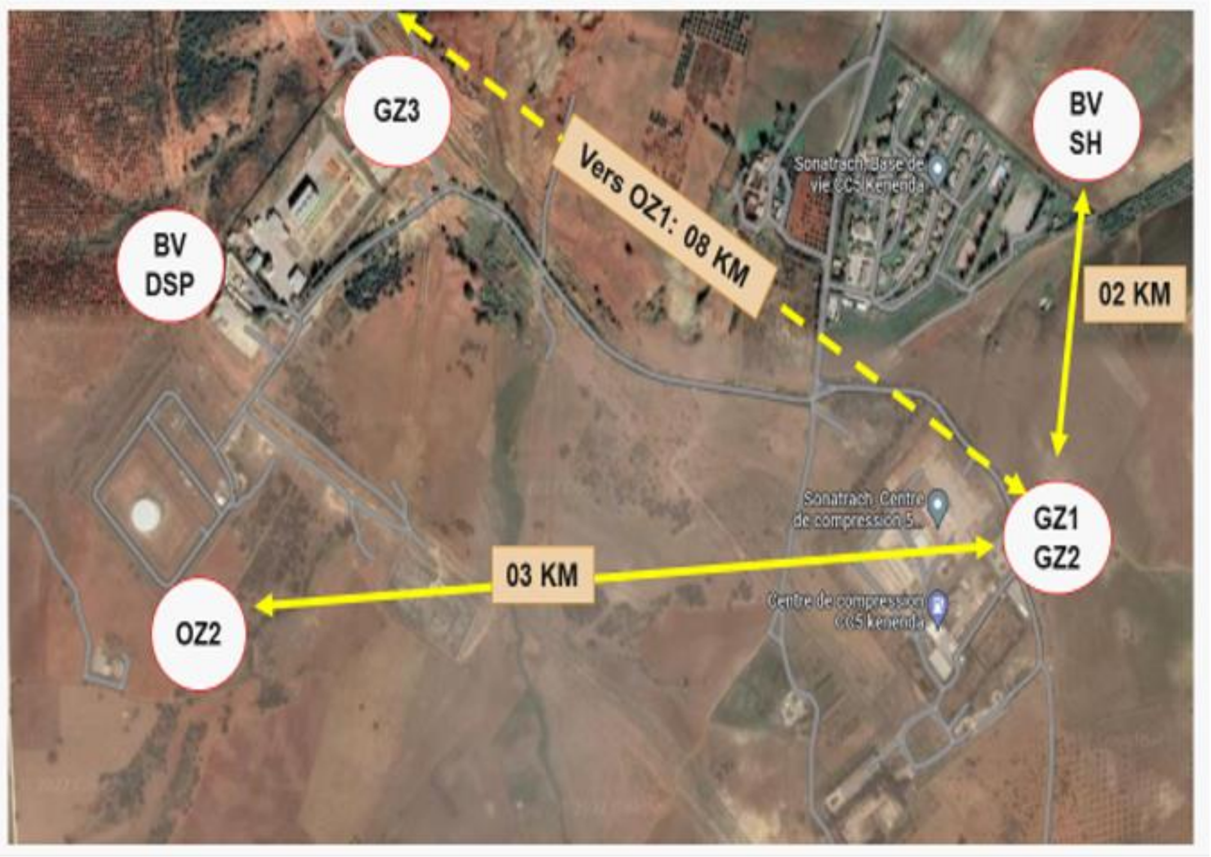
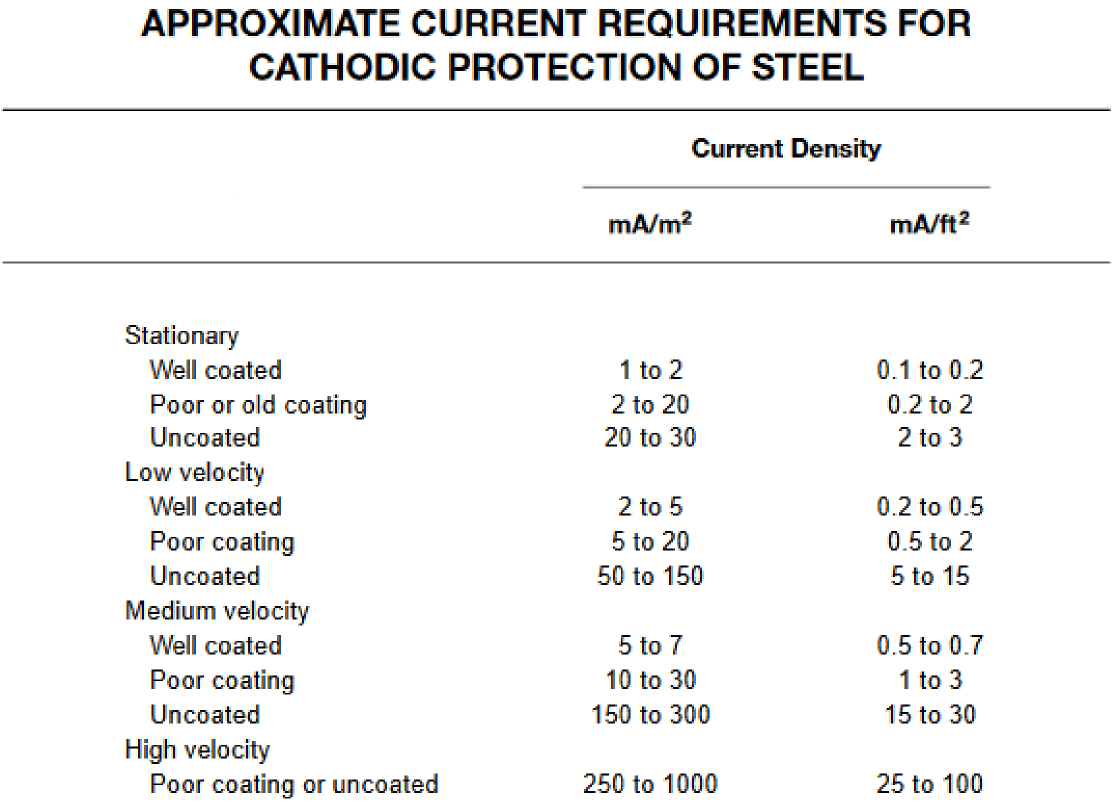
r=                      % radius of the tank
i0=                     % current density for 30 degrees
T=                      % operating temperture
Ig=                     % current output of the anode
l=                      % width of the anode
Rcl=                    % linear reistance of distrubution bars
Lt=                     % total length of the anodes
N=                      % number of anodes
Cres=                   % cables resistance
D=                      % diameter of the tank
fc=                     % correction factor for the number of anodes
H=                      % wetted surface
fdet=                   % deteriration factor
K=                      % number of anodes
c=                      % water resistivity
Lchapelet=              %length of a single anode wire
```

Appendix E

Geographical location of the fire-fighting tanks



Appendix F



APPROXIMATE CURRENT REQUIREMENTS FOR CATHODIC PROTECTION OF STEEL

	Current Density	
	mA/m^2	mA/ft^2
Stationary		
Well coated	1 to 2	0.1 to 0.2
Poor or old coating	2 to 20	0.2 to 2
Uncoated	20 to 30	2 to 3
Low velocity		
Well coated	2 to 5	0.2 to 0.5
Poor coating	5 to 20	0.5 to 2
Uncoated	50 to 150	5 to 15
Medium velocity		
Well coated	5 to 7	0.5 to 0.7
Poor coating	10 to 30	1 to 3
Uncoated	150 to 300	15 to 30
High velocity		
Poor coating or uncoated	250 to 1000	25 to 100