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**Presented by:**

**Mohammed Ali Djani and Ibrahim Hider**

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**Haoud El-Hamra SONATRACH**

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**In front of the jury composed of:**

**Lotfi BAAMEUR**

**Asst.Prof. (UKM Ouargla)**

**President**

**Amel GUERDOUH**

**Asst.Prof. (UKM Ouargla)**

**Examiner**

**Oussama BACHA**

**Assoc.Prof. (UKM Ouargla)**

**Supervisor**

**University year: 2022/2023**

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## Dedication

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

To my parents,

your unconditional love, belief in my potential, and relentless support have been the driving force behind my achievements. Your sacrifices, both big and small, have enabled me to pursue my dreams and reach for academic excellence. I am forever grateful for your unwavering guidance, endless patience, and countless sacrifices that have brought me to this point.

Dear brothers, although you may be younger, your enthusiasm and eagerness to learn have encouraged me to become a better role model, I dedicate this thesis to you, with the hope that it will inspire you to pursue your own passions and embrace the journey of knowledge.

Mohammed Ali



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## Dedication

بسم الله الرحمن الرحيم

“I dedicate this note to my dear father, who has always been my source of support and inspiration, and who helped me achieve this achievement.”

“I thank my professors, who provided me with the knowledge and experiences that will continue in my career.”

“I thank my classmates, who shared this experience with me and supported me throughout my studies.”

“I thank my family and friends, who have always been by my side and supported me every step of the journey.”

Ibrahim



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## Abbreviations

**LPG:** Liquefied petroleum gas.  
**API:** American Petroleum Institute  
**CP:** Cathodic Protection  
**AC:** Alternating Current  
**DC:** Direct Current  
**Cu/CuSO<sub>4</sub>:** Copper/Copper (II) Sulfate  
**Fe<sup>2+</sup>:** Ferrous Ion  
**Fe<sup>3+</sup>:** Ferric Ion  
**FeO<sub>3</sub>:** Iron Oxide (magnetite)  
**Fe<sub>3</sub>O<sub>4</sub>:** Magnetic Iron Oxide  
**H<sub>2</sub>O:** Water Molecule  
**O<sub>2</sub>:** Oxygen molecule (Gas)  
**OH<sup>-</sup>:** Hydroxide  
**Zn<sup>2+</sup>:** Zin Ion  
**H<sub>2</sub>:** Hydrogen Atom (Gas)  
**pH:** Potential of Hydrogen  
**SO<sub>4</sub><sup>2-</sup>:** Sulfate ion  
**Cu:** Copper  
**Cl:** Chlorine  
**AgCl:** Silver chloride  
**Hg:** Mercury  
**Hg<sub>2</sub>Cl<sub>2</sub>:** Mercurous Chloride  
**KCl:** Potassium Chloride

## الملخص

تهدف هذه الدراسة الشاملة إلى استكشاف تطبيق الحماية الكاثودية في مجال نقل المحروقات، يختص هذا النوع من الحماية في منع التآكل واهتراء الانابيب النفط والغاز التي تعتبر البنية التحتية لشركة سوناطراك، نتطرق في هاته الدراسة للجوانب المختلفة لأنظمة الحماية الكاثودية، بما في ذلك تصميمها وتقييم أدائها وتحسينها كما يتم تحليل العوامل المؤثرة على كفاءة النظام بدقة، مثل مقاومة التربة وسلامة الطلاء الواقي وتداخل التيارات الشاردة، وذلك من خلال استخدام قياسات ميدانية وتجارب معملية

اما فيما يخص طرق الفحص والكشف عن التآكل، فتستخدم عدة تقنيات منها تقنية تسرب التدفق المغناطيسي (MFL) واساليب الفحص عن طريق الموجات فوق الصوتية، وذلك لقدرة على تحقيق نتائج دقيقة قابلة للتحليل والاستنباط،

نختم بحثنا هذا ببعض التجارب المخبرية التي من شأنها ان تعزز جودة أدوات القياس المعتمد عليها من قبل قسم الحماية الكاثودية بمديرية حوض الحمراء.

**كلمات مفتاحية:** الحماية الكاثودية - التآكل - الصدأ - الأنود - الكاثود - التيار الكهربائي - الانابيب والهياكل المعدنية - أنواع التآكل - الأكسدة والارجاع

## Résumé

Cette étude exhaustive se penche sur l'application de la protection cathodique dans l'industrie pétrolière et gazière, en mettant spécifiquement l'accent sur la prévention de la corrosion au sein de l'infrastructure de Sonatrach. La recherche examine différents aspects des systèmes de protection cathodique, incluant leur conception, l'évaluation de leurs performances et leur optimisation. Les facteurs influençant l'efficacité des systèmes, tels que la résistivité du sol, l'intégrité du revêtement et les interférences des courants parasites, sont minutieusement analysés grâce à des mesures sur le terrain, des expérimentations en laboratoire et des simulations.

Les méthodes de détection et d'inspection de la corrosion, y compris la technologie de MFL (Magnetic flux leakage) et les tests ultrasoniques, sont explorées quant à leur applicabilité et leur fiabilité dans les efforts de protection de l'entreprise.

Nous concluons cette recherche avec quelques expériences de laboratoire qui amélioreraient la qualité des outils de mesure approuvés par le Département de la protection cathodique dans le district du Haoud El Hamra.

**Mots clé :** Protection cathodique ; Corrosion ; Anode ; Courant électrique ; pipelines et les structures métalliques.

## Abstract

This comprehensive study examines the application of cathodic protection in the oil and gas industry, focusing specifically on corrosion prevention within Sonatrach's infrastructure. The research examines various aspects of cathodic protection systems, including their design, performance evaluation, and optimization. Factors influencing the effectiveness of these systems, such as soil resistivity, coating integrity, and interference from stray currents, are carefully analyzed through field measurements, laboratory experiments, and simulations.

Corrosion detection and inspection methods, such as MFL (Magnetic Flux Leakage) technology and ultrasonic testing, are explored for their applicability and reliability in corporate protection efforts.

In conclusion, the research proposes laboratory experiments aimed at improving the quality of measurement tools approved by the Department of Cathodic Protection in the Haoud El Hamra district

**Keywords:** Cathodic protection; Corrosion prevention; MFL; Ultrasound; Sacrificial anodes; Electric Potential.

## **General introduction**

Petroleum products are moved through pipelines from their origin to various points such as refining, storage, and distribution. In Algeria, SONATRACH operates the pipeline transportation of hydrocarbons (crude oil, condensate, natural gas & LPG) on a network of approximately 18512 km.

The pipelines made of API-grade steel are typically buried structures with depths ranging from 0.6 to 2.5 meters, and are protected from corrosion through various treatments like Cathodic protection, surface treatments, and modification of the corrosive environment by adding corrosion inhibitors. However, more than 95% of micro-alloyed steels are still susceptible to corrosion that occurs on the outer surface of pipelines due to material interactions with the corrosive soil environment.

Despite efforts to protect these pipelines from corrosion, internal and external corrosion continues to be a major challenge globally, especially in the petroleum industry. It is estimated that about 15% of annual steel production is lost each year, resulting in the destruction of approximately 5 tons of steel per second.

Localized corrosion is a form of damage that can occur in pipelines when they are exposed to aggressive media. It develops by forming a galvanic corrosion pile between the exterior, passive, and Cathodic surface, and the inside of the pit, active and anodic, resulting in a cavity that can quickly become deep even though only a small amount of metal dissolves globally. This type of corrosion is particularly dangerous when it comes to short lines.

This study focuses on investigating the cathodic protection system of the pumping station at Haoud el Hamra. Despite the dual protection of pipeline steel with passive protection by coatings and cathodic protection by imposed current, the risk of corrosion is inevitable. Corrosion failures, particularly by pitting corrosion, can occur, which has motivated our research in this area.

The methodology of this study involves recording potential measurements for some lines. Chapter 1 presents a theoretical study of corrosion and its various forms, while Chapter 2 focuses on cathodic protection and the different protection methods, as well as the necessary steps to safeguard our structure. Chapter 3 covers pipeline maintenance, including the equipment and methods used to detect and control internal or external corrosion.

Finally, we conclude our study with scientific experiment and some recommendations.

**CHAPTER I:  
CORROSION AND MEANS OF  
PROTECTION**

## **I. Introduction**

Corrosion is a critical problem that can be found in all industries worldwide. Corrosion is particularly severe in the oil and gas industry due to the large quantities of metallic based assets located throughout the entire supply chain. The oil and gas sectors consumed a considerable percentage of the total global corrosion cost, which exceeded US\$2.5 trillion in 2016

In this chapter we are going to learn more about corrosion and how we could minimize its negative impact.

### **I.1. Corrosion**

Corrosion refers to the destructive process in which a metal is chemically or electrochemically attacked by its environment. However, physical deterioration caused by non-chemical factors, such as erosion, galling, or wear, is not classified as corrosion. In certain cases, there can be a combination of chemical attack and physical deterioration, resulting in terms like corrosion-erosion, corrosive wear, or fretting corrosion. It's important to note that corrosion, as defined here, specifically pertains to the chemical attack on metals, excluding nonmetals from this definition. While nonmetals like plastics may undergo swelling or cracking, wood may split or decay, granite may erode, and Portland cement may leach away, the term corrosion, as used in this book, exclusively refers to the chemical attack on metals. The term "rusting" is specifically used for the corrosion of iron or iron-based alloys, leading to the formation of corrosion products primarily composed of hydrous ferric oxides. Nonferrous metals, therefore, are subject to corrosion but do not undergo rusting. [1].

### **I.2. The Social and Economic Effects of Corrosion**

Corrosion can cause decreased safety, increased maintenance costs, reduced efficiency, and economic losses, all of which can have significant social and economic effects. We mention few of them:

#### **I.2.1. Economic Consequences**

When considering the costs of corrosion, it is important to differentiate between direct and indirect costs. Direct costs encompass expenses related to inspection, maintenance, protective measures, premature replacement of structures, and the use of more expensive construction materials. Indirect costs primarily involve production losses resulting from shutdowns during repairs or maintenance. They also include product losses due to leaks, reduced efficiency caused by corrosion-coated pipes or blockages from corrosion products. Product contamination leading to reduced usability or value can also contribute to significant economic losses. Indirect costs

of corrosion can also be seen as costs resulting from excessive design precautions. Factors such as limited knowledge of practical corrosion rates, a lack of confidence in control measures, or unnecessarily large safety margins often result in the selection of thicker or more expensive materials than strictly necessary. Additionally, the loss of potential returns due to higher investments in corrosion control is considered an indirect cost.[2].

### **I.2.2. Social Consequences**

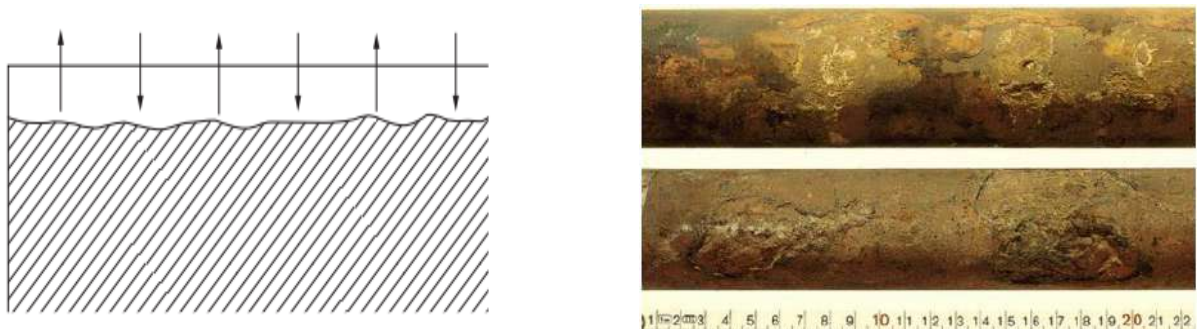
Corrosion also has a social dimension. In recent years, there has been an increasing recognition that our global reserves of energy and raw materials are not limitless. Corrosion leads to the annual loss of significant amounts of material. It is estimated that approximately 10% of the world's steel production, equivalent to around  $5 \times 10^7$  tons per year, is specifically used to replace corroded steel. It's important to note that once metal has corroded, it is completely lost and cannot be recycled. The use of recycled metal greatly reduces the energy consumption in steel manufacturing, highlighting how corrosion results in additional energy consumption. By controlling corrosion, we can contribute to the conservation of energy and raw materials. Additionally, the consequences of corrosion extend to more severe losses, such as the incalculable economic and personal impacts on health and even loss of life due to equipment failures (e.g., explosions) or structural degradation caused by corrosion in transportation systems (e.g., aircraft). Effective corrosion prevention measures can help limit these economic, social, and personal losses.[2].

### **I.3. Forms of Corrosion**

Design engineers must be well-versed in environmental factors and specific corrosion types. Recognizing potential corrosion hazards and being familiar with mitigation methods is vital for their work.

#### **I.3.1. Uniform Corrosion**

Uniform corrosion, also referred to as general corrosion, occurs uniformly across the entire surface of the metal. This is due to the even distribution of anodic and cathodic reactions across the surface **Figure I-1**.



**Figure I-1:** Uniform corrosion [2].

Uniform corrosion is the most prevalent and significant form of corrosion, particularly in terms of weight loss. Its consistent nature and relatively predictable rate enable reasonably accurate lifetime predictions. Consequently, general corrosion does not pose any significant technical challenges, and it allows for the application of a "corrosion allowance." [2].

### I.3.2. Localized Corrosion

In all other cases, the attack is more localized as a result of the presence of heterogeneous situations. The essence of localized corrosion is that fixed anodic sites on the surface can be indicated where the oxidation reaction dominates, surrounded by a cathodic zone where the reduction reaction takes place. Localized corrosion is far more treacherous in nature and far less readily predictable and controllable, and it is also capable of leading to unexpected damage with disastrous consequences.

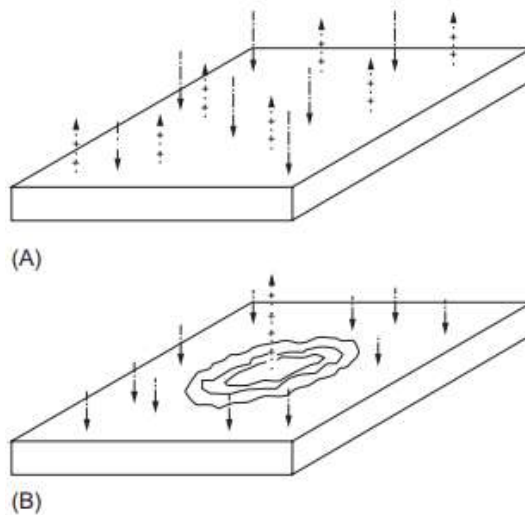


Figure I-2: Difference between uniform (A) and localized (B) corrosion [2].

Figure I-2 demonstrates the contrast between uniform corrosion (A) and localized corrosion (B). In uniform corrosion, the anodic and cathodic partial currents are evenly distributed across the surface. However, in localized corrosion, the oxidation reaction is confined to specific areas. Regardless of the type, the overall charge of the oxidation process remains equal to the charge of the reduction process, calculated over the entire surface [2].



Figure I-3: Images of Localized corrosion [2].



### I.3.3. Galvanic Corrosion

When two metals with varying potentials come into contact within a conductive electrolyte solution, it leads to an increased corrosion rate on the anodic metal and a decreased corrosion rate (thus providing protection) on the cathodic metal. This type of corrosion, referred to as galvanic corrosion, is also known as contact or bimetallic corrosion. (Figure I-4)[2].

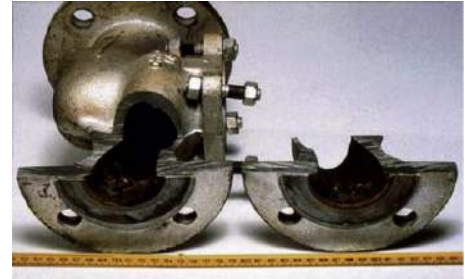
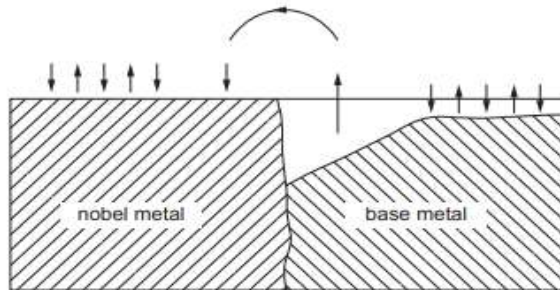


Figure I-4:Galvanic Corrosion [2]

### I.3.4. Crevice Corrosion

Crevice corrosion is a prevalent type of corrosion that affects active-passive metals, especially those that are sensitive. It typically occurs in areas where there is a small amount of stagnant electrolyte solution, such as between flanges, bolts, nuts, etc. (see Figure I-5).

The mechanism is represented as follows: Take, for example, two metal plates (M), which are riveted together and are located in aerated seawater (Ph=7). The overall reaction consists of the dissolution of metal M and the reduction of oxygen to hydroxide ions [2]:

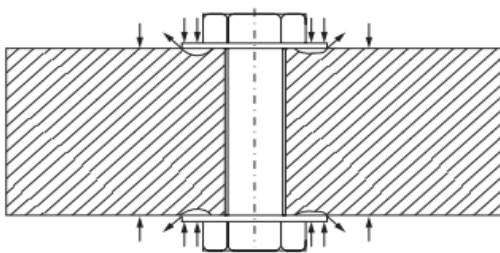
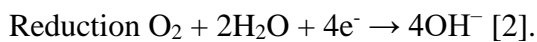


Figure I-5: Crevice Corrosion [2].

### I.3.5. Pitting Corrosion

Pitting corrosion is a hazardous type of localized corrosion that can lead to the formation of holes in the metal. It is challenging to detect pitting corrosion due to the small size of the pits and their tendency to be covered by corrosion products. (Figure I-6)[2].

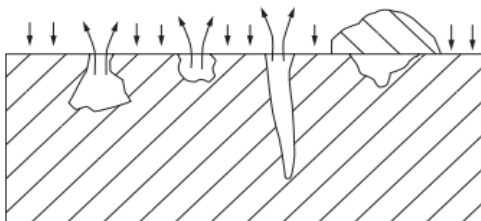


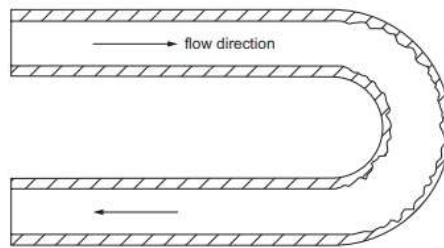
Figure I-6:Pitting Corrosion [2].

### **I.3.6. Intergranular Corrosion**

Metals consist of tiny crystals or grains, where the surface of one grain is next to another, creating grain boundaries. In specific circumstances, areas near the grain boundaries can become highly reactive, often more so than the majority of the grains, due to their more anodic nature. Corrosion can then penetrate the metal through these grain boundaries, resulting in a type of corrosion known as intergranular (or intercrystalline) corrosion [2].

### **I.3.7. Erosion Corrosion**

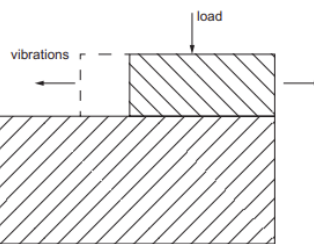
Erosion corrosion refers to the intensified deterioration or increased damage to a metal caused by variances in the velocity between a corrosive fluid and the metal surface. Typically, this velocity is high, and it often involves mechanical wear and abrasion effects. Erosion corrosion occurs when there is turbulent flow at a specific location due to disturbances in the flow pattern, such as downstream of a constriction, obstacle, or bend in a pipe[2].



*Figure I-7: erosion corrosion Diagram [2].*

### **I.3.8. Fretting Corrosion**

Fretting corrosion is a type of corrosion that takes place when two surfaces are in contact with each other and, despite being seemingly stationary, experience small periodic movements. (Figure I-8)[2].



*Figure I-8: Fretting Corrosion Diagram [2].*

### **I.3.9. Stress Corrosion**

There are two types of corrosion characterized by the formation of cracks in the metal that penetrate inward, generally perpendicular to the surface. These types of corrosion result from the combined effects of the metal, its surrounding environment, and mechanical stress. Stress corrosion cracking is caused by a sustained tensile strain applied to the surface, and it is identifiable by its branching crack pattern. Stress corrosion can manifest as either intergranular or transgranular cracking. [2].

**I.4. Factors influencing corrosion**

The factors listed here have been organized in a framework of six categories with a number of subfactors as shown in **Table I-1**. According to Staehle’s materials degradation model, all engineering materials are reactive and their strength is quantifiable[3].

*Table I-1: Factors Influencing corrosion [3].*

Factor	Subfactors and Contributing Elements
<b>Material</b>	Chemical composition of alloy Crystal structure Grain boundary (GB) composition Surface condition
<b>Environment</b> <i>Chemical definition</i> <i>Circumstance</i>	Type, chemistry, concentration, phase, conductivity Velocity, thin layer in equilibrium with relative humidity, wetting and drying, heat transfer boiling, wear and fretting, deposits
<b>Stress</b> <i>Stress definition</i> <i>Sources of stress</i>	Mean stress, maximum stress, minimum stress, constant load/constant strain, strain rate, plane stress/plane strain, modes I, II, III, biaxial, cyclic frequency, wave shape Intentional, residual, produced by reacted products, thermal cycling
<b>Geometry</b>	Discontinuities as stress intensifiers Creation of galvanic potentials Chemical crevices Gravitational settling of solids Restricted geometry with heat transfer leading to concentration effects Orientation vs. environment
<b>Temperature</b>	At metal surface exposed to environment Change with time
<b>Time</b>	Change in GB chemistry Change in structure Change in surface deposits, chemistry, or heat-transfer resistance Development of surface defects, pitting, or erosion Development of occluded geometry Relaxation of stress

## **I.5. Means of protection**

### **I.5.1. Corrosion Protection by Coatings**

Coatings are considered the first line of defense against corrosion in the underground pipeline industry. The amount of corrosion protection provided by a particular coating system depends on many variables. There are a variety of coating types and each has advantages and disadvantages that must be considered when selecting a coating, especially when using CP [4].

### **I.5.2. Cathodic protection (CP)**

CP is a technique to reduce corrosion on a metal surface by making the entire surface (to be protected) a cathode, which means it will be receiving protective current and cannot be corroding. DC is forced onto all surfaces of the pipeline. There are many issues with applying and monitoring CP. These will be discussed in detail in later chapters. Bear in mind that CP can protect the pipeline only if it can actually find a path to it. An electrical shield can be defined as any barrier (disbonded coatings, rocks, metal, etc.) that will prevent or divert from a pipeline, for which protection is intended, the flow of CP current from soil or water.

Anodic protection [4].

### **I.5.3. Anodic Protection**

Anodic protection can be applied on materials with a well-defined and reliable passive region and low passive current density, in contrast to cathodic protection, anodic protection is relatively new. The feasibility of anodic protection was first demonstrated in 1954 and tested on a small-scale stainless-steel boiler designed to handle sulfuric acid [23]. Anodic protection refers to the corrosion protection achieved by maintaining an active-passive metal or alloy in its passive state by applying an external anodic current [3].

### **I.5.4. Protection by corrosion inhibitors**

To control or minimize the corrosion of metallic surfaces, chemical compounds can be introduced into the corrosive medium. This method of corrosion control is known as inhibition, and the added compounds are referred to as corrosion inhibitors. These inhibitors work by reducing the rate of either anodic oxidation, cathodic reduction, or both processes. Upon application, the inhibitors form a protective film on the metal surface. It is believed that the inhibitors are adsorbed onto the metal surface through either physical (electrostatic) adsorption or chemisorption. The adsorbed inhibitor then acts to decrease the corrosion rate of the metal surface by impeding the anodic dissolution reaction, the cathodic evolution of hydrogen, or both mechanisms [5].

### I.6. Electrochemical classification of metals

The following table presents standard potentials measured relative to the normal hydrogen electrode (NHE), at a temperature of 25°C and a pressure of 1 atm [5].

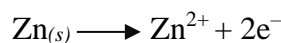
*Table I-2 : Standard potentials of metals [5].*

<u>Active</u>		<u>Inert</u>	
Electrode	E°	Electrode	E°
<b>Li/Li<sup>+</sup></b>	-3.01	Mo/Mo <sup>3+</sup>	-0.2
<b>Rb/Rb<sup>+</sup></b>	-0.298	Sn/Sn <sup>2+</sup>	-1.140
<b>Cs/Cs<sup>+</sup></b>	-0.292	Pb/Pb <sup>2+</sup>	-0.126
<b>K/K<sup>+</sup></b>	-2.92	H <sub>2</sub> /H <sup>+</sup>	±0
<b>Ba/Ba<sup>2+</sup></b>	-2.92	Bi/BiO <sup>+</sup>	+0.32
<b>Sr/Sr<sup>+</sup></b>	-2.89	Cu/Cu <sup>2+</sup>	+0.34
<b>Ca/Ca<sup>+</sup></b>	-2.84	Rh/Rh <sup>2+</sup>	+0.6
<b>Na/Na<sup>+</sup></b>	-2.71	Hg/Hg <sup>+</sup>	+0.798
<b>Mg/Mg<sup>2+</sup></b>	-2.38	Ag/Ag <sup>+</sup>	+0.799
<b>Th/Th<sup>4+</sup></b>	-2.10	Pd/Pd <sup>2+</sup>	+0.83
<b>Ti/Ti<sup>2+</sup></b>	-1.75	Ir/Ir <sup>3+</sup>	+1.0
<b>Be/Be<sup>2+</sup></b>	-1.70	Pt/Pt <sup>2+</sup>	+1.2
<b>Al/Al<sup>3+</sup></b>	-1.66	Au/Au <sup>3+</sup>	+1.42
<b>V/V<sup>2+</sup></b>	-1.5	Au/Au <sup>+</sup>	+1.7
<b>Mn/Mn<sup>2+</sup></b>	-1.05		
<b>Zn/Zn<sup>2+</sup></b>	-0.763	O <sub>2</sub> /OH <sup>+</sup>	+0.401
<b>Cr/Cr<sup>3+</sup></b>	-0.71	I <sub>2</sub> /I <sup>-</sup>	+0.536
<b>Fe/Fe<sup>2+</sup></b>	-0.44	Br <sub>2</sub> /Br <sup>-</sup>	+1.066
<b>Cd/Cd</b>	-0.402	Cl <sub>2</sub> /Cl <sup>-</sup>	+1.256
<b>In/In<sup>3+</sup></b>	-0.34	F <sub>2</sub> /F <sup>-</sup>	+2.85
<b>Ti/Ti<sup>+</sup></b>	-0.335	S/S <sup>2-</sup>	-0.51
<b>Co/Co<sup>2+</sup></b>	-0.27	Se/Se <sup>+2</sup>	-0.78
<b>Ni/Ni<sup>2+</sup></b>	-0.23	Te/Te <sup>2+</sup>	-0.92

### I.7. Link between electrolytes and metals

Electrolytes and metals are linked in the sense that some metals can act as electrolytes under certain conditions. When a metal is placed in an electrolyte solution, such as a saltwater solution, it can dissolve and release metal ions into the solution. These metal ions can then conduct electricity and participate in electrochemical reactions, just like the ions of other electrolytes.

For example, when a zinc electrode is placed in an electrolyte solution containing zinc ions (such as a solution of zinc sulfate), the zinc ions can migrate from the solution to the electrode and deposit on its surface. This process, known as electrodeposition, can be used to coat metals with a layer of another metal, such as copper plating on a steel surface.



I.7.1. Electroneutrality

As this process goes on, the electrons which remain in the zinc cause a negative charge to build up within the metal which makes it increasingly difficult for additional positive ions to leave the metallic phase. A similar buildup of positive charge in the liquid phase adds to this inhibition. Very soon, therefore, the process comes to a halt, resulting in a solution in which the concentration of  $Zn^{2+}$  is still too low (around  $10^{-10}$  M) to be detected by ordinary chemical means [6].

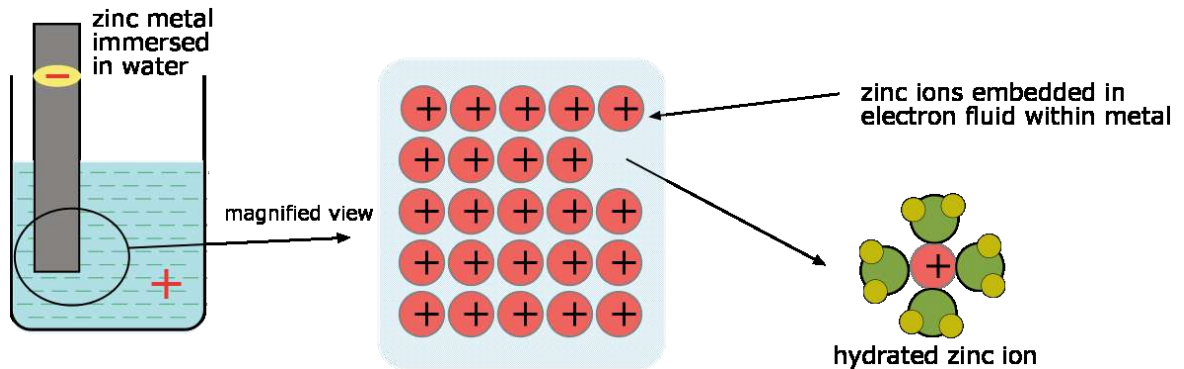


Figure I-9: Oxidation of metallic zinc in contact with water [6].

I.7.2. Potential differences at interfaces

The interface between two phases includes a transitional region known as the electric double layer, which exhibits charge imbalance. This double layer comprises an inner monomolecular layer of adsorbed water molecules and ions, along with an outer diffuse region that counterbalances any local charge disparity, gradually merging into the random arrangement of the bulk solution. When a metal is immersed in pure water, the presence of an electron fluid within the metal causes polar water molecules to adsorb onto the surface and align themselves, resulting in the formation of two thin planes with positive and negative charges. In the presence of dissolved ions in the water, certain larger and more polarizable anions tend to weakly bond (chemisorb) to the metal, generating a negative inner layer, which is offset by an excess of cations in the outer layer.

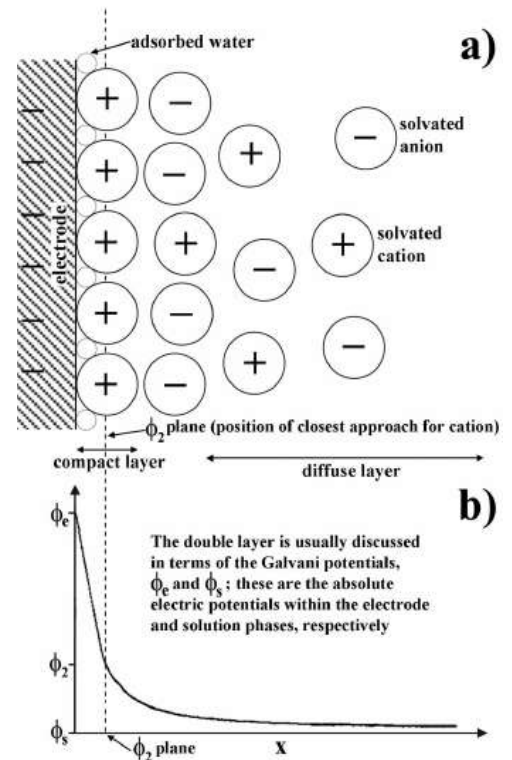


Figure I-10: Electrical double layer near a negatively charged electrode surface. a) A simplified schematic of its structure. b) Potential vs. distance profile [6].



Interfacial potential differences are not directly observable. The usual way of measuring a potential difference between two points is to bring the two leads of a voltmeter into contact with them. It's simple enough to touch one lead of the meter to a metallic electrode, but there is no way you can connect the other lead to the solution side of the interfacial region without introducing a second electrode with its own interfacial potential, so you would be measuring the sum of two potential differences. Thus single electrode potentials, as they are commonly known, are not directly observable [6].

### I.8. Electrochemical cells

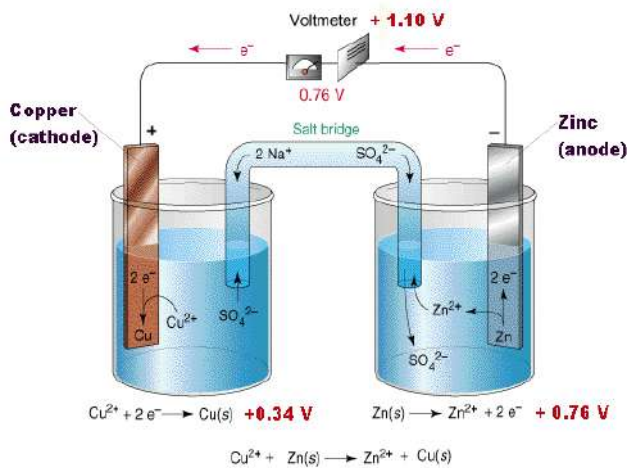
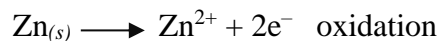


Figure I-11: A simple electrochemical [6].

The cell consists of two compartments divided by a porous barrier, which permits the passage of ions while preventing significant mixing of the two solutions. When the two electrodes are connected, charges move in the indicated directions. It is important to note that the accumulation of positive charge on the left side can be counterbalanced either by the diffusion of  $\text{Zn}^{2+}$  ions to the right or, to a lesser extent, by the movement of  $\text{Cl}^-$  ions to the left.

This configuration is known as a galvanic cell. A typical setup involves two metal pieces, such as zinc and copper, each immersed in a solution containing a dissolved salt specific to the respective metal. The two solutions are separated by a porous barrier that restricts rapid mixing but allows ion diffusion. Without further intervention, negligible reaction would occur. However, when the zinc and copper electrodes are connected using a metallic conductor, the surplus electrons resulting from the dissolution of  $\text{Zn}^{2+}$  ions in the left cell can flow through the external circuit and reach the right electrode. There, they can be transferred to the  $\text{Cu}^{2+}$  ions, causing them to undergo "discharge" and form Cu atoms on the surface of the copper electrode. The overall reaction remains the same as before—the oxidation of zinc by copper (II) ions:  $\text{Zn}_{(s)} + \text{Cu}^{2+} \rightarrow \text{Zn}^{2+} + \text{Cu}_{(s)}$ . However, in this setup, the oxidation and reduction processes occur at separate locations [6]:



I.9. Reference electrodes

In most electrochemical experiments, our focus is primarily on one of the electrode reactions. However, since all measurements must involve a complete cell comprising two electrode systems, it is customary to utilize a reference electrode as the complementary half of the cell. A reference electrode must fulfill certain key criteria, including ease of preparation and maintenance, as well as stable potential. The latter requirement specifically necessitates that the concentration of any ionic species involved in the electrode reaction remains constant. The commonly employed approach to achieve this is by employing an electrode reaction that involves a saturated solution of an insoluble salt containing the desired ion. One such system that satisfies these conditions is the silver-silver chloride electrode, which has been mentioned earlier:



The reference electrode typically consists of a silver wire coated with AgCl. To create this coating, the silver is made the anode in an electrolytic cell that contains HCl. At the silver surface, Ag<sup>+</sup> ions promptly react with Cl<sup>-</sup> ions, resulting in the formation of AgCl.

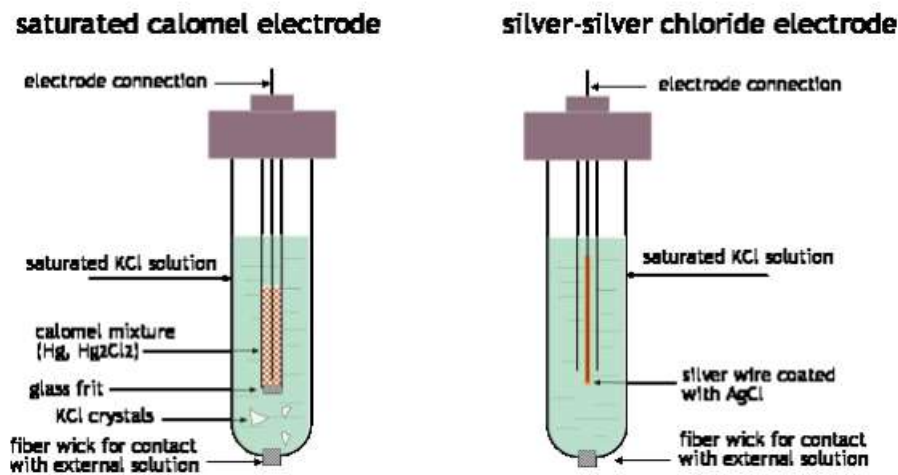


Figure I-12: Reference electrode: the silver-silver chloride and calomel electrodes [6].

Another commonly used reference electrode is the calomel electrode, which consists of mercury(I) chloride, commonly known as calomel. The electrode setup is represented as  $\text{Hg} \mid \text{Hg}_2\text{Cl}_{2(s)} \mid \text{KCl} \parallel \dots$ . The electrode reaction is  $\text{Hg}_{(l)} + \text{Cl}^{-} \longrightarrow 1/2 \text{Hg}_2\text{Cl}_{2(s)} + \text{e}^{-}$ . Both the silver-silver chloride and calomel electrodes have their potentials accurately determined against the hydrogen electrode. However, the hydrogen electrode is not commonly employed in routine electrochemical measurements due to the more intricate preparation process, which involves special treatment of the platinum surface through preliminary electrolysis. Additionally, the need for a supply of hydrogen gas adds to the inconvenience and potential hazards involved [6].



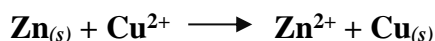
### I.10. The Nernst equation

The standard cell potentials discussed earlier pertain to cells where all dissolved substances have a unit activity, equivalent to an "effective concentration" of 1M. Likewise, any participating gases are considered to have an effective pressure (referred to as fugacity) of 1 atm. If these concentrations or pressures deviate from these standard values, the cell potential will change, and the extent of this change can be predicted based on the principles you are already familiar with.

For instance, let's consider a scenario where we decrease the concentration of  $Zn^{2+}$  in the Zn/Cu cell from its standard effective value of 1M to a much lower value:



This will reduce the value of Q for the cell reaction



Consequently, this change increases the spontaneity of the reaction, as predicted by the Le Châtelier principle, driving it towards the right. As a result, the free energy change ( $\Delta G$ ) becomes more negative than the standard free energy change ( $\Delta G^\circ$ ), leading to a more positive value for the actual cell potential (E) compared to the standard potential ( $E^\circ$ ). The relationship between E and  $E^\circ$  is established by starting with the previous Equation, which correlates the standard free energy change for the complete conversion of products into reactants with the standard potential.

$$\Delta G^\circ = -nFE^\circ$$

By analogy we can write the more general equation

$$\Delta G = -nFE = 0$$

We can now substitute these values into the expression that connects  $\Delta G$  and  $\Delta G^\circ$ , which you may remember from the chapter on chemical equilibrium. This expression calculates the change in free energy for any degree of reaction, encompassing all possible values of the reaction quotient Q.

$$\Delta G = \Delta G^\circ + RT \ln Q$$

Which gives

$$-nFE = -nFE^\circ + RT \ln Q$$

which can be rearranged to:

$$E = E^\circ - \frac{RT}{nF} \ln Q$$

The Nernst equation is more commonly written in this form and for 25°C [6]:

$$E = E^\circ - 0.06 \ln Q$$

### **I.11. Conclusion**

In conclusion, corrosion is a complex phenomenon that can have detrimental effects on various materials, structures, and industries. In this chapter, we have explored the different factors that contribute to corrosion, including environmental conditions, material properties, and electrochemical reactions. By understanding these factors, we can better mitigate and prevent corrosion from occurring.

However, our exploration does not end here. In the next chapter, we will delve into the concept of cathodic protection. This technique has proven to be an effective method for mitigating corrosion in various applications. We will study the principles behind cathodic protection and its different implementation methods. By equipping ourselves with this knowledge, we can further enhance our understanding and ability to combat the destructive forces of corrosion.

Through continued research and the application of innovative techniques like cathodic protection, we can strive towards preserving the integrity and longevity of materials and structures, ensuring a safer and more sustainable future.

# **Chapter II:**

# **Cathodic Protection**

## II. Introduction

In this chapter, we will introduce the concept of cathodic protection, which is a technique used to control the corrosion of a metal surface by making it the cathode of an electrochemical cell, thereby reducing the corrosion rate. This method is commonly used in industries such as oil and gas, marine, and transportation to protect pipelines, ships, and other metal structures from corrosion. Cathodic protection can be achieved through two methods: sacrificial anode and impressed current systems. Both methods involve the use of an external current source to drive the electrochemical reactions and protect the metal structure.

### II.1. Cathodic protection fundamentals

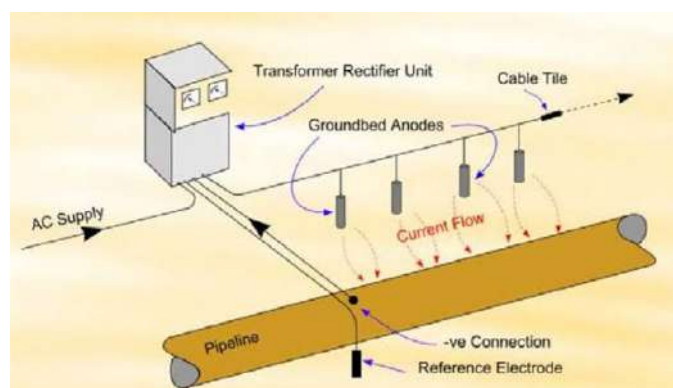
Cathodic protection is a method used to stop metal from corroding when it comes into contact with an electrolyte (such as water, soil, or concrete). It works by reducing the corrosion potential of the metal to a level where the corrosion rate is significantly slowed down. This is achieved by applying a voltage that provides enough cathodic current to the metal surface, lowering its potential to a level where the rate of corrosion is low enough. This process is called "polarization." When the potential change to the negative direction, it is called "cathodic polarization." This technique reduces the oxidation rate of the metal and increases the reduction reaction of the oxidizing species in the electrolyte, ultimately protecting the metal structure[7].

### II.2. Cathodic protection mechanisms

The cathodic protection current can be applied in one of two ways:

#### II.2.1. Impressed current protection

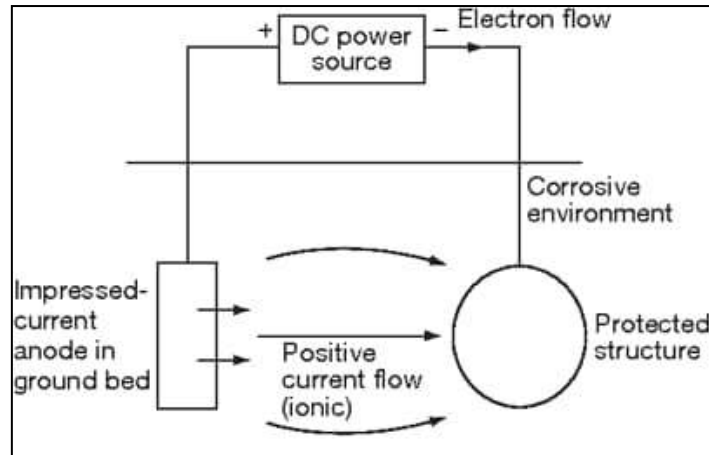
Impressed current cathodic protection installations use an electrical power supply to polarize the structure to be protected through the circulation of direct current between the structure and an auxiliary anode known as a "Groundbed anodes." This method is illustrated in the accompanying **Figure II-1** [8].



*Figure II-1: Principle of cathodic protection by impressed current [08].*

### II.2.2. Galvanic cathodic protection

When certain metals or alloys are placed in the same electrolytic medium as the structure that needs protection, they have a lower electrode potential (as measured in relation to a reference electrode) than the structure's metal. By connecting the lower potential metal to the structure, its potential tends to increase while the structure's metal decreases, resulting in a decrease in corrosion rate. This method is shown in the accompanying **Figure II-2** [8].



*Figure II-2: Principle of cathodic protection by galvanic anodes [18].*

### II.3. Comparison of cathodic protection by sacrificial anodes (CPSA) and impressed current (CPIC)

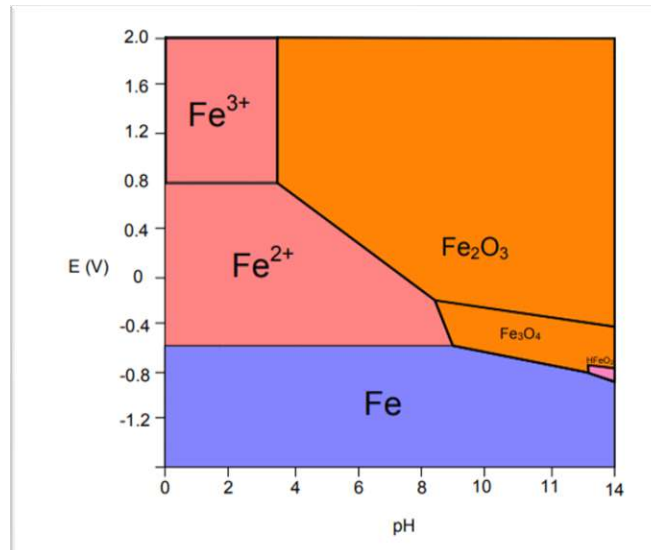
*Table II-1: Comparison between the two cathodic protection methods [9].*

	CPSA	CPIC
<b>Installation</b>	Simple	Complex
<b>Maintenance</b>	No maintenance	Requires maintenance
<b>External source</b>	Non	Yes
<b>Driving voltage</b>	Fixed	Variable
<b>Current requirement</b>	Limited and low	Variable and high
<b>Soil conductivity</b>	High	Wide range

## II.4. Pourbaix diagram

A Pourbaix diagram, also known as a potential-pH diagram, shows in which areas an element exists or dominates on an E-pH plane. These diagrams are created using thermodynamic data.

**Figure II-3** provides an example of a simplified Pourbaix diagram for iron[10].



*Figure II-3: Pourbaix diagram of iron (at 25°C) [19].*

Based on the diagram presented in the Figure above, iron can exist in three different thermodynamic states, determined by its potential and the pH level of the solution it is in. These states are:

- Thermodynamic passivation, which occurs when the iron is within the stability ranges of ferrous or ferric hydroxides ( $\text{Fe}_2\text{O}_3$ );
- Activity or corrosion, which occurs in the ferrous and ferric ion stability domains ( $\text{Fe}^{3+}$ ,  $\text{Fe}^{2+}$ , and Fe at extreme pH levels);
- Immunity, which is the area of the diagram that corresponds to the stability of iron (Fe)[10].

When iron is in the corrosion domain, it dissolves in the solution and forms soluble salts and hydroxides.

In the passivation domain, iron is protected by a surface film that isolates it from the surrounding environment. This is an area where the metal is shielded from the solution as long as the film has formed uniformly and remains attached, and nothing mechanically destroys it. The area of immunity is where iron remains in its metallic state and, therefore, cannot corrode, as oxidation reactions are no longer possible. This is the field of cathodic protection[11].

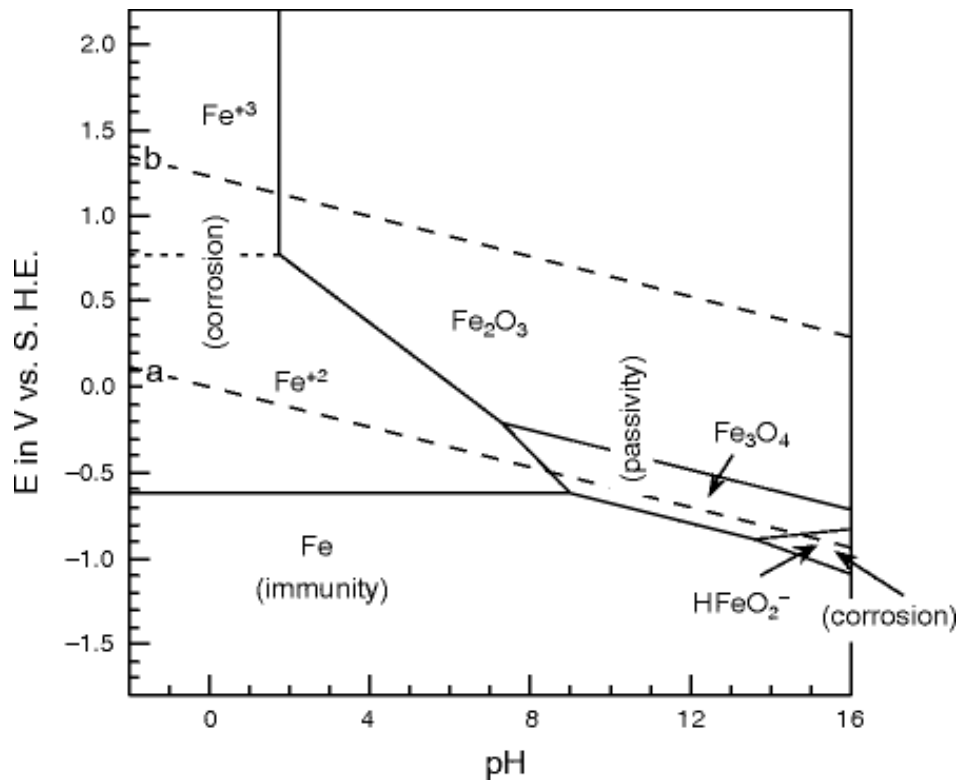


Figure II-4: Iron-Water diagram At 25°C considering only Fe, Fe<sub>3</sub>O<sub>4</sub>, Fe<sub>2</sub>O<sub>3</sub> as solid bodies [20].

## II.5. Cathodic protection potential measurement

It is about applying a potential lower than the protection potential so that the corrosion rate is reduced  $E \leq E_{prot}$

The cathodic protection potential is given by the Nernst equation:

$$E_{prot} = E^{\circ} + \frac{RT}{nF} \ln 10^{-6}$$

At room temperature (25°C), this expression becomes:

$$E_{prot} = E^{\circ} - 0.354 n \text{ (V/ENH)}$$

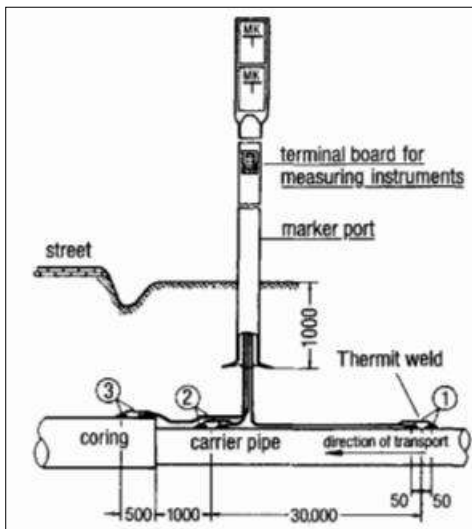
It is accepted and standardized that the PC potential threshold for buried steel is

➤ **0.85 V/(Cu/CuSO<sub>4</sub>)** in an airy environment.

➤ **0.95 V/(Cu/CuSO<sub>4</sub>)** for deaerated soils. These values were measured against a copper sulphate electrode.

### II.5.1. Test stations

Test stations are necessary for measuring pipe and soil potentials, pipe currents, and the resistances of insulating connections and casings. Potential test stations should have a maximum spacing of 1 to 3 km, and every fifth test station should be designed as a pipe-current test point. In built-up areas, the spacing of test stations should be reduced to about 0.5 km. At the initial point of long, branched pipelines, it is recommended that pipe-current test stations be installed so that the current consumption of this pipeline can be controlled. The installation of pipe-current test stations before insulating is advisable in order to determine internal electrolytic bridging, which can lead to the destruction of insulating connections. In general NYY-O cable is used with a minimum copper cross-section of 2 x 2.5 mm. The cable is connected to the pipeline by a suitable process, and the connections are carefully coated. The cable is usually connected to aboveground test stations and covered with hoods, tiles or a cable ribbon[12].



*Figure II-5: Aboveground test stations, potential measuring points (2) and (3), pipe current measuring point (1/2).*

### II.5.2. Distribution of test stations

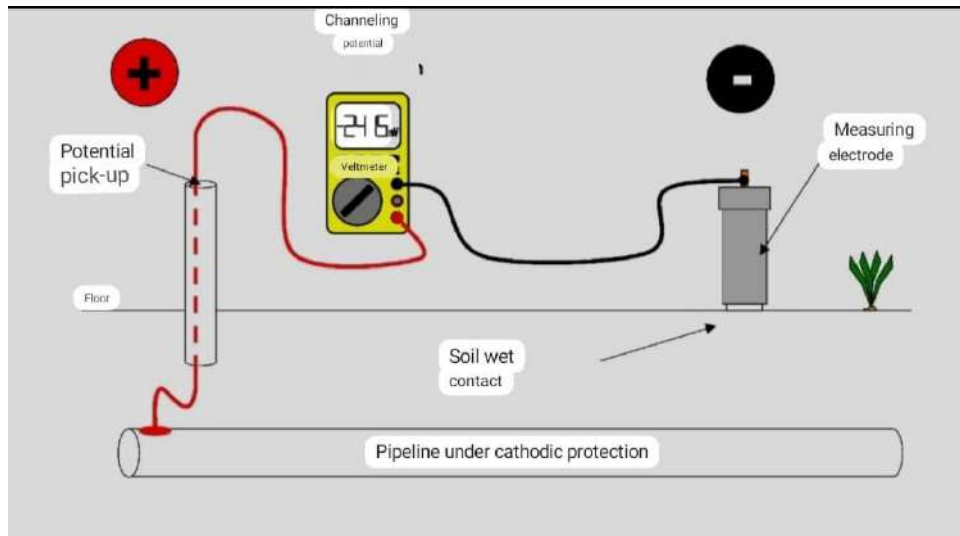
The placement of sockets for protection varies depending on the installation and geographical conditions. The distance between these points can range from a few hundred meters to 10 km. The selection of these points is based on several criteria, such as:

- Accessibility (located near a road or motorable path),
- Soil resistivity (in areas with less resistant and more aggressive soil, increased monitoring is necessary),



- River crossings (wadis).
- Crossing with other metal pipes or parallelism.
- Crossing of telecommunication cables.
- Electrified railway crossings.
- A passage under a metal sheath (one grip on the condition, one grip on the tube), or antenna end.

If there are no particular points to consider, a distance of 3 km between two potential taps is sufficient for effective control of the protected driving[13].



*Figure II-6: Mounting required for a close-space survey [13].*

### II.5.3. The protection current density

The current density is the ratio of the current received by a metal coupon to its surface area:

*i*: Current density in mA/m<sup>2</sup>

I: Quantity of current in mA

S: Control surface in m<sup>2</sup>

On the other hand:

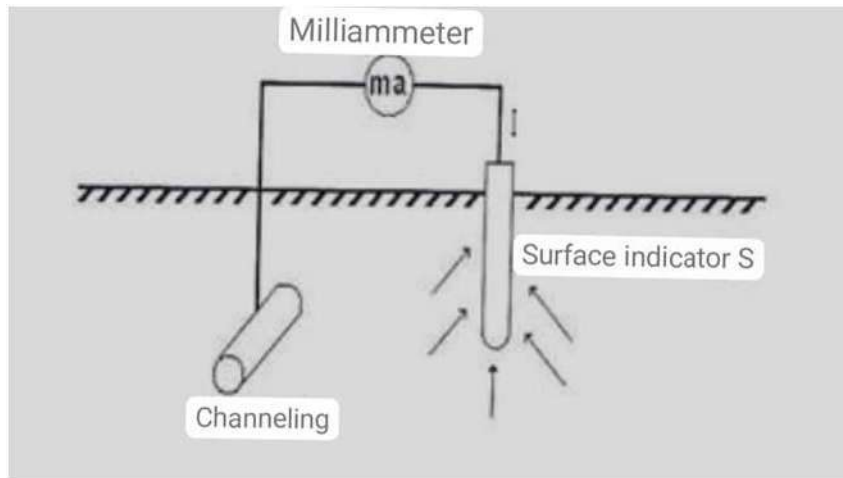
$$i = \frac{E_{rep} - E_{prot}}{R_{is}}$$

As:

Natural potential  $E_{rep}$  of steel = - 0.4 V/(Cu/CuSO<sub>4</sub>)

$E_{prot}$ : threshold potential of the line in protection=-1 V.

$R_{iS}$ : insulation resistance in  $2.m^2$  of the structure considered.



*Figure II-7: Measurement principle [09].*

The method is simple, but the value of the current density thus measured depends on the following:

- The geometric shape of the metal coupon.
- Of the surface of the metal coupon.
- Current application time.
- Of the metal that constitutes the coupon.

The current densities obtained from experiments provide steel with the necessary protection against damage:

- (0.7 mA/m<sup>2</sup>): for bare steel in cement.
- (5 mA/ m<sup>2</sup>): for bare steel in an anaerobic soil without bacteria.
- (35 mA/m<sup>2</sup>): for bare steel in aerated soil.
- (60 mA/m<sup>2</sup>): for bare steel in rough fresh water.
- (100 mA/m<sup>2</sup>): for bare steel in calm sea water.
- (400 mA/m<sup>2</sup>): for bare steel in an anaerobic environment with sulfate-reducing bacteria.

These values are averages and must always be adjusted according to the actual characteristics of the soils encountered[14].

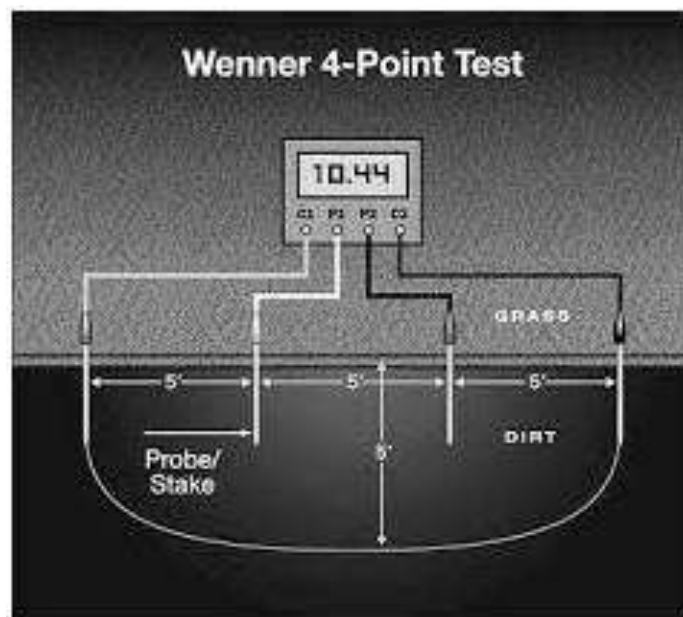
## II.6. Soil resistivity

The soil surrounding the pipe plays a crucial role in the corrosion process. It allows the flow of electrons and corrosion current and influences the formation of anodic zones and the rate of corrosion at these points in the pipe. If the electrons can move easily through the soil, the corrosion rate increases, leading to faster destruction of the pipe. The soil's composition, humidity, permeability, porosity, salt or other contaminants content, and dissolved gas presence all contribute to the heterogeneity of the soil, promoting corrosion. Additionally, fluctuations in the soil due to seasonal and climatic changes, variations in biological activity, and the water table level all encourage corrosion[15].

### II.6.1. Soil resistivity measuring method:

To determine the resistivity of the ground, the four-probes method (also known as the Wenner method) measures the distance between electrodes inserted into the ground. This provides an estimate of the ground's total resistivity at a depth of at least three-quarters ( $3/4$ ) the distance between the electrodes. Here is how the method works:

- 1- Bring the ground resistance meter with four (04) earth probes and a connection cable.
- 2- Plant the four probes respecting the equidistance (distance "a") between the probes. The distance "a" must be a function of the burying depth of the conduit "h" with " $h = 3/4 a$ ";[15].



*Figure II-8: principle of soil resistivity measurement by Wenner's method (a- distance between two probes, b- depth of insertion of the probes) [15].*

### II.6.2. Resistivity calculation

The formula for the resistivity value:

$$\rho = 2 \times a \times \pi \times R \dots\dots (2.1)$$

$\rho$  = soil resistivity in ( $\Omega$ .m).

$a$  = distance between posts in (m).

$R$  = resistance, value read on the ground meter ( $\Omega$ ).

- Connect the four rods to the earth meter, respecting the order of connection from closest to farthest.
- Make sure that the four inputs of the earth meter are de-shunted.
- Read the resistance value on the earth meter display.
- Calculate according to formula (1) the value of the soil resistivity[10].

*Table II-2: numerical examples of resistivities.*

Soil resistivity in $\Omega$ .cm	Soil corrosivity
<b>Under 500</b>	<b>Very severe</b>
<b>500 To 2000</b>	<b>Severe</b>
<b>2000 To 5000</b>	<b>High</b>
<b>5000 To 10 000</b>	<b>Moderate</b>
<b>10 000 To 25 000</b>	<b>Average</b>
<b>25 000 To 50 000</b>	<b>Light</b>
<b>Supérieure Then 50 000</b>	<b>Low</b>

### II.7. Rectifier station

The extraction station typically uses a transformer powered by a low-voltage electrical network (220-380 V). However, when low-voltage electricity is unavailable, alternative energy sources such as solar power, batteries, generators, and thermo-generators must be used. The ideal substation location offers the most effective protection over a wide range with the least amount of power required. Various factors, including the shape and length of the network, conduit diameter, soil aggressiveness, optimal weir installation points, availability and cost of electrical power, and subsoil obstruction by other structures, determine this. The overall network plan must be examined to properly size the cathodic protection system and determine the most suitable locations for pipelines and electric lines[15].



*Figure II-9: rectifier station.*

### **II.7.1. Types of transformer rectifiers in terms of cooling systems**

- **Air cooling (AN)**

This type of transformer rectifier is typically manufactured in the range of 10 to 50 volts and 5 to 30 amps, but on demand, the design and production of cool air transformer rectifiers are also possible at higher power[16].

- **Oil cooling (ON)**

In order to increase the reliability of the device in harsh conditions, transformer rectifiers are manufactured with oil cooling. In this type of transformer rectifiers, the rectifier bridge and filters are immersed in the oil and the oil tank is equipped with surface display, oil temperature and Dehumidifiers[16].

### **II.7.2. Power source**

The power source includes the following[16]:

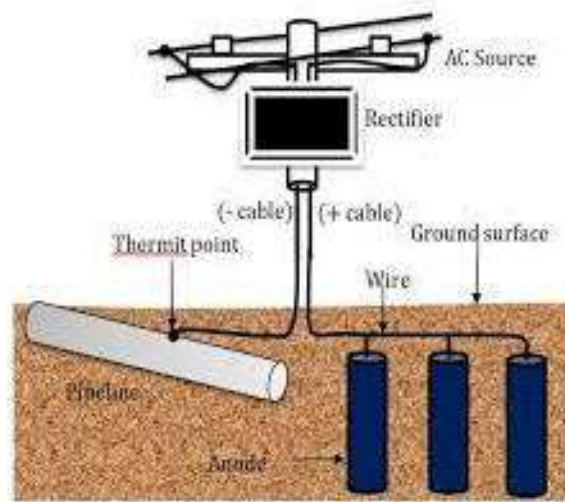
- Local distribution network
- Photovoltaic panels that provide electrical energy are used for PCCI
- Thermoelectric generators
- Wind turbines.
- With the possibility of using batteries in the future such as lithium batteries.
- Fluid driven turbines.
- Turbogenerators.

## II.8. Realization of ground beds

### II.8.1. Surface ground bed

**Horizontally laid anodes:** This installation method should be used when the surface resistivity of the soil is low and when there is enough space on the ground. It is recommended, for example, when using old rails or similar-shaped scrap metal.

**Vertically laid anodes:** It is still a surface ground bed, but the anodes are buried vertically in holes at the bottom of the trench where the cables are laid. The anodes are thus located at a depth of between one and two meters, and depending on the nature of the soil, in wetter soil than on the surface[11].



*Figure II-10: Anode installation method [09].*

### II.8.2. Deep ground beds

This type of ground bed is used when:

- It is impossible, by a surface weir, to obtain a suitable distribution of the current on the surface to be protected;
- There is a risk of too much interference on the neighboring structures.
- The resistivity of the soil on the surface does not allow to obtain an acceptable value.

The process consists in drilling a hole with a steel casing made of a tube with an internal diameter generally between 120 and 200 mm.

The casing must be made as the drilling progresses, the tubes being welded end to end.

It is recommended to measure the contact resistance of the casing every 5 m, for example. The depth at which the measured resistance decreases significantly is considered favorable:

- Drill below this depth to accommodate all the anodes provided;
- Insert the anodes into the borehole (several electrically independent strings are to be made up), ensuring that the anodes are held in place by a rot-proof rope and not by the electric cables
- Fill the space between the anodes and the casing with graphite (if the tube is empty of water) or iron shot[11].

### II.9. Calculations of Number of Anodes Required and Spacing

The number of anodes required for a pipe or any bare structure can be conveniently estimated as per example given below. Suppose 10 000 ft of a bare 4-inch pipeline is to be protected and if the resistance of soil is 1000 ohms per cubic centimeter, the pipe requires 1 mA/ft<sup>2</sup> for protection. The anode output curve shows 100 mA per anode in this type of soil. The number of anodes can be easily calculated as shown below[17]:

➤ **Calculations**

a) *First calculate the area of the pipe:*

$$\text{Area} = \frac{4 \times 3.14 \times 10000}{12} = 10500 \text{ft}^2$$

$$\text{Total current requirement} = 10\ 500 \times 1.0 = 10\ 500 \text{ mA}$$

Number of anodes required

$$= \frac{\text{Total current required}}{\text{Current output of a single anode}} = \frac{10500 \text{ mA}}{100 \text{ mA/anode}} = 95 \text{ anodes}$$

b) *Total current requirement =*

$$\text{Protected area (m}^2\text{)} \times \text{Current density (A/m}^2\text{)}$$

Or

$$\text{Protected area (ft}^2\text{)} \times \text{Current density (m A/ft}^2\text{)}$$

c) *Total weight of anode material required:*

$$\frac{\text{Current (A)} \times \text{Design life (years)} 8760}{\text{Capacity A - h/kg}}$$

## II.10. Factors limiting the effectiveness of cathodic protection

Cathodic protection is an effective way to control corrosion in water environments. However, certain factors can limit its effectiveness, including:

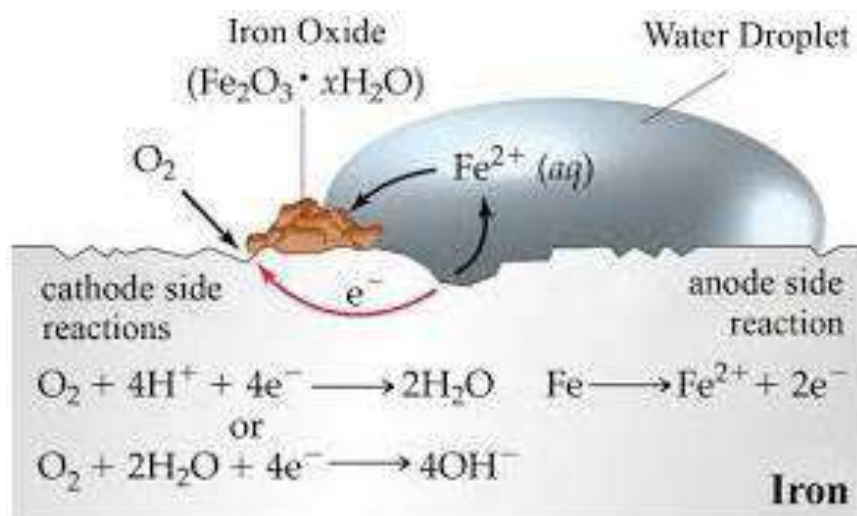
- Insufficient electrical continuity of the system,
- The loss of adhesion of the coatings,
- The influence of cathodic protection between adjacent metallic structures
- The influence of a direct current source,
- The influence of an alternating current source

The regular monitoring and maintenance operations of the cathodic protection system make it possible to monitor these influencing factors and maintain the effectiveness of the protection system over time[11].

### II.10.1. Coating adhesion failure

The failure of adhesion of the coatings associated with the cathodic protection can occur when these coatings do not resist the alkalization of the medium created by the cathodic reactions. Therefore, the choice of the appropriate coating is based, above all, on good feedback from experience.

Poor adhesion of the coating, or a degraded coating with several defects, directly influences the need for protection current, hence the efficiency of the cathodic protection[11].



*Figure II-11: Diagram of the formation of a cathodic disbandment [22].*



### II.10.2. The influence of a direct current source

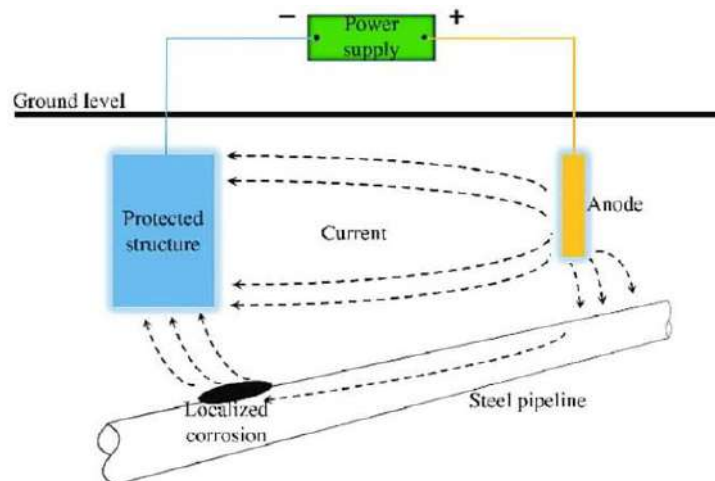
Poorly insulated DC installations can cause electrical leakage currents in the ground, especially near electrified railway lines. These stray currents vary in intensity, direction, and path over time, and they can create a hazard for nearby structures. In addition, the currents lead to the formation of two electrolysis cells, which can cause corrosion in pipes when the stray current moves from the structure to the rail. To combat stray currents, it is possible to insulate the source emitting them or use passive or active limitation devices.

#### Passive:

- Polarized ground faults that facilitate the evacuation of currents that have taken a pipe.

#### Active

- Current regulation or drainage system that limits the transit current [11].



*Figure II-12: Corrosion by stray currents [23]*

### II.10.3. The influence of an alternating current source

Recommendations and measurements are given to assess the risk of corrosion:

Perform electrode potential measurements of the structure with appropriate equipment to ensure that the potential criteria are met in the presence of AC current on the structure;

The probability of corrosion may be negligible if the AC current density relative to a bare surface of 1 cm<sup>2</sup> is less than 30 A/m<sup>2</sup> and if the electrode potential of the structure meets the cathodic protection criteria;

On cathodically protected structures subject to the presence of alternating current, a higher protective current density may be necessary to achieve the protective potential;

Structures with small minor coating defects may have a higher risk of AC corrosion[11].

## **II.11. Conclusion**

Cathodic protection is a well-established technique used to protect metal structures from corrosion, and it has been employed in various industries, such as oil and gas, marine, and transportation, among others. Despite its widespread use and effectiveness in preventing corrosion, there are some drawbacks to this method that must be considered.

One of the main limitations of cathodic protection is that it is a passive technique that relies on the continuous availability of a direct current to maintain the protected metal structure's corrosion protection. Any interruption in the power supply, whether intentional or accidental, could result in immediate and rapid corrosion of the protected metal. This means that regular monitoring and maintenance of the cathodic protection system are required to ensure its proper function and avoid any potential failure.

Another concern with cathodic protection is the environmental impact of the sacrificial anodes used in the system. The materials used to create sacrificial anodes, such as zinc or aluminum, can have negative environmental effects if not properly handled and disposed of. Furthermore, as the anodes corrode and degrade, they may release metals and chemicals into the environment, which can harm wildlife and ecosystems. The proper handling and disposal of spent anodes is critical to minimizing environmental damage.

Moreover, cathodic protection is not always a practical or cost-effective solution for preventing corrosion. For example, in some cases, the installation of a cathodic protection system may be technically difficult or economically unfeasible due to the location or size of the structure being protected. In such cases, alternative corrosion protection methods may need to be considered.

In conclusion, while cathodic protection has proven to be an effective method for preventing the corrosion of metal structures, it is not without its limitations. Its reliance on a continuous power supply, potential environmental impact, and limitations in practicality and cost-effectiveness in some situations may make it a less desirable solution for certain applications. Therefore, careful consideration of the potential drawbacks of cathodic protection should be taken into account when evaluating the most appropriate corrosion protection method for a given application.

**Chapter III:**  
**Cathodic Protection Evaluation in**  
**Practice**

### III. Introduction

This chapter delves into the practical implementation of cathodic protection, showcasing its effectiveness in combating corrosion and preserving the integrity of vital infrastructure. It explores key aspects such as system measurements, corrosion detection and inspection methods, The insights shared in this chapter are based on firsthand experience gained during an internship at Sonatrach, a renowned organization in the field of oil and gas.

#### III.1. HEH regional transport directorate

One of the key Sonatrach locations is the base of Haoud El Hamra, also known as HEH. In fact, it serves as a crossroads for transporting liquid hydrocarbons from Algeria's southern ports to its northern refineries. The Hassi-Messaoud crude oil deposit was found in 1956. The first pipeline, known as "Baby-Pipe," had a 6" diameter and was 170 km long. It connected Hassi-Messaoud and Touggourt. From there, a tanker took the crude oil to the port of Skikda for export.

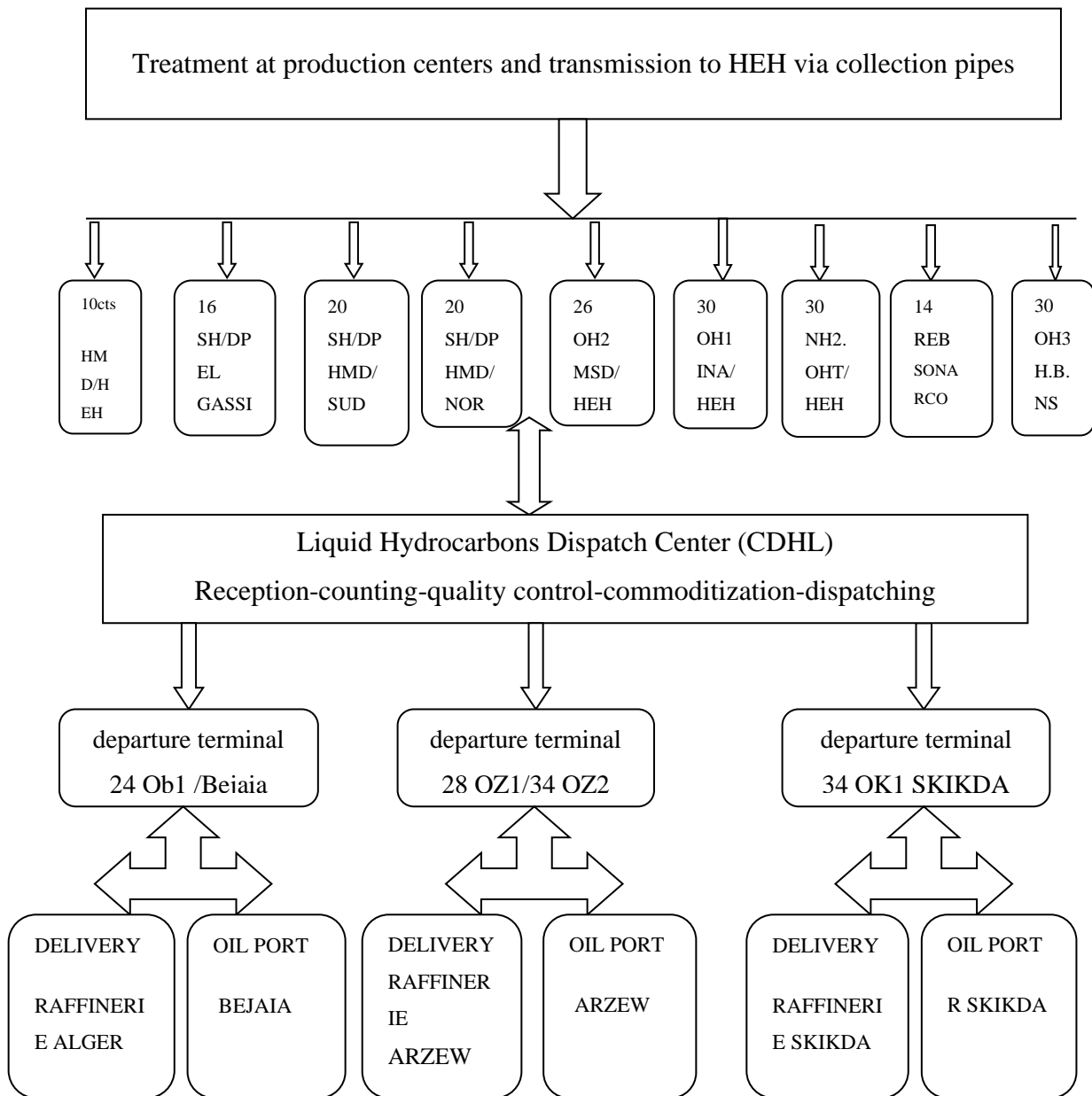


*Figure III-1: Houd El Hamra 1956*

The French Oil Company opened the HEH site in 1959 with the commissioning of the OB1 pipeline, which connects Haoud El-Hamra and Bejaia. As time went on, it became more and more familiar with the construction of the 28" OZ1 line (801 km) connecting HEH to Arzew (1965), the 34" OK1 line to Skikda (1972), and finally, the 34" SK1 line (OZ2 line) coming after the OZ1 (2003). The Regional Guidance 26 kilometers north of Hassi Messaoud, Haoud El-Hamra is situated 66 kilometers southeast of the wilaya of Ouargla's capital. It occupies about 3.5 km<sup>2</sup> of space. An estimate places the built area at 6.5 hectares (0.0065 km<sup>2</sup>). It's crucial to remember that Haoud El-Hamra serves as more than just the location of the TRC Branch.

The RTH region's missions are as follows:

- The collection of liquid and gaseous hydrocarbons from oil fields via collection networks operated by the CDHL for crude oil and condensate and the CNDG of Hassi R'mel for gases.
- quantification of these hydrocarbons.
- quality control of the received products.
- storage of liquid hydrocarbons in storage tanks.
- shipment of liquid products by pipelines to the marine terminals



### III.2. Description and importance of the OB1 24" pipe

The HEH/BEJAIA pipe initially operated only with three pumping stations for a maximum flow equal to 1800 m<sup>3</sup>/h and later a fourth station was built which bears the name SP1Bis next to DJEMAA which made it possible to increase the flow. up to 2200 m<sup>3</sup>/h

Around 1967, oil needs increased, hence the obligation to put the four satellite stations SPA-SPB-SPC-SPD online to increase the flow rate to 2540 m<sup>3</sup>/h according to the request from the BEJAIA terminal...

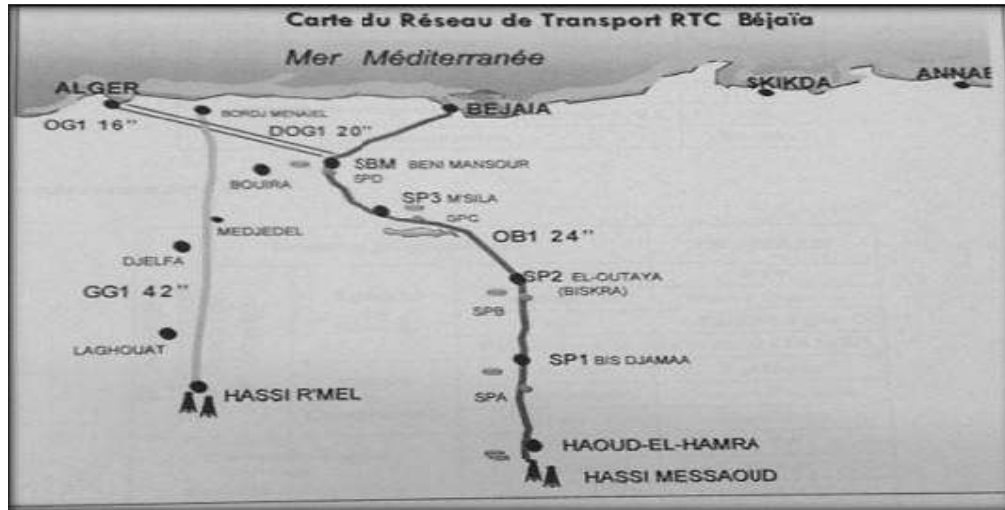


Figure III-2: bejaia rtc transport network map

#### III.2.1. Characteristics of the pipe section used in this study

Table III-1: Our pipe characteristics to this study

Pipe: PS8/GEM – SP1 bis/OB1	
Diameter	24" (60.96 cm)
Starting from	Sp1 HEH
Ending in	Sp1 bis Djamaa
Overall length (L)	189.83 Km
Steel grade	X52
Thickness	12.7
Exterior coating	coal tar pitch and PE (Polyethylene)
External surface / km	360724 km
Period in years (t)	25 years

**III.2.2. The properties of API 5L X52 steel grade**

*Table III-2: the properties of API 5L X52 steel presented in SI unit*

Property	Value
Minimum Yield Strength	360 MPa
Minimum Tensile Strength	460 MPa
Elongation	≥ 21%
Hardness	207 HB maximum
Chemical Composition	Carbon (C): 0.16% max Manganese (Mn): 1.65% max Phosphorus (P): 0.020% max Sulfur (S): 0.010% max Silicon (Si): 0.45% max Chromium (Cr): 0.40% max Nickel (Ni): 0.40% max Copper (Cu): 0.40% max Molybdenum (Mo): 0.15% max Vanadium (V): 0.08% max
Heat Treatment	Normalized
Weldability	Excellent
Formability	Good
Applications	Oil and gas pipelines

### III.3. Calculating the number of rectifiers:

The rectifier is a direct-current generator. It usually consists of a transformer-rectifier fed from the 220V low-voltage electrical grid.

Transformer-rectifier substations are of the 60 volt - 30-amp continuous output type, supplied with 230 volt single-phase 50 Hz alternating current.

The units are wall-mounted. The dimensions of the enclosures are: 800 x 600 x 300 mm.<sup>3</sup>

For the number of rectifiers,  $N_r$  to be installed, we use the following equation:

$$N_r = \frac{L}{L_r} \quad (3.1)$$

$L$ : Length of pipe surface to be protected (m).

$L_r$ : The protection range of the rectifier (m).

The following formula is used to evaluate the protection range of the rectifier  $L_r$ :

$$L_r = \frac{1}{a} \cdot \ln \left( \left( \frac{E_s}{E} \right) + \sqrt{\left( \left( \frac{E_s}{E} \right)^2 - 1 \right)} \right) \quad (3.2)$$

$a$ : Structure attenuation coefficient ( $m^{-1}$ ).

$E_s$ : Injection potential at protection point.

$E$ : Metal potential without protection (The spontaneous potential of the pipe without cathodic protection).

$$a = \sqrt{\frac{r}{R}} \quad (3.3)$$

$r$ : Longitudinal resistance of the pipe. ( $\Omega/m$ ).

$$r = \frac{\delta_a}{\pi \cdot \tau \cdot (D_{ext} - \tau)} \quad (3.4)$$

$R$ : Transverse resistance of the pipe. ( $\Omega/m$ ).

$$R = \frac{R_{is}}{\pi \cdot D_{ext}} \quad (3.5)$$

$\delta_a$ : Steel resistivity ( $21 \cdot 10^{-8} \Omega/m$ ).

$D_{ext}$ : The outer diameter of the pipeline

$\tau$  : Pipeline Thickness

$R_{is}$ : Insulation resistance given by coating ( $18360 \Omega/m$ ).



For the calculation of the resistances  $r$  and  $R$ , we will take the following diameter and thickness of our pipe which is  $D_{ext}$ : 24" (0.6096 m) |  $\tau$ : 12.7mm (0.0127 m). We will have:

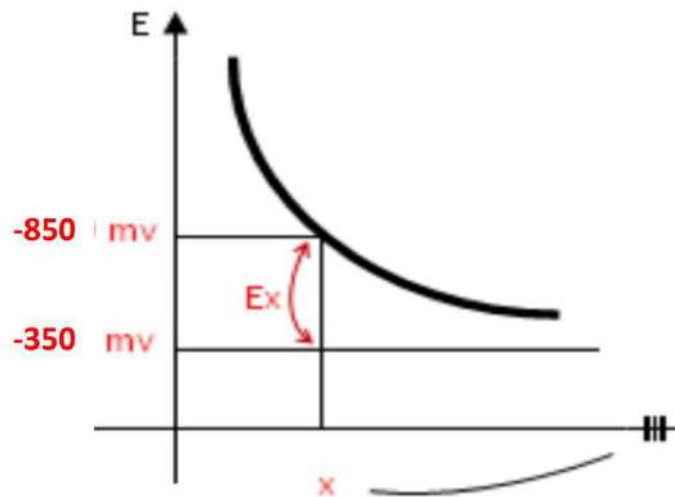
$$r = 0.882 \cdot 10^{-5} \Omega/m;$$

$$R = 0.96 \cdot 10^4 \Omega/m;$$

And then, substituting the values of  $r$  and  $R$  into equation (3.3), we get:

$$a = 0.303 \cdot 10^{-4} m^{-1}$$

The metal potential in the soil without cathodic protection is -380mV. As shown in **Figure III-3**, with cathodic protection, the new potential becomes (-850mv).



*Figure III-3: Change in potential due to cathodic protection*

The higher the insulation value, the lower the attenuation factor, and the greater the protection range. Conversely with a large attenuation factor, the range of the rectifier is reduced.

From equation (3.2), the reach of the rectifying units will be :

$$L_r = 43km$$

According to equation (3.1), the number of filling stations will be :

$$N_r = \frac{(L_{HEH-sp1(bis)})}{L_r} = \frac{189.83}{43}$$

$$N_r = 4.41 = 4 \text{ rectifiers}$$

### III.3.1. Calculating the protection's current

The protection's current is released into the ground by the anodic bed, disperses within the soil, and returns to the pipe. This flow of current results in a reduction in potential within the pipe. By hypothesis, the cathodic protection is sized for a current density of 0.5mA/m<sup>2</sup>

The calculation required to protect the overall external surface of the pipeline is determined as follows:

*Ps: we calculated for 5km only.*

$$I_{tot} = d \times S_p = I \times (S_{HEH-SP1 bis}) \quad (3.6)$$

**d:** Maximum current density (A/m<sup>2</sup>).

**S<sub>p</sub>:** Surface to be protected (m<sup>2</sup>).

$$I_{tot} = 0,0005 \times 9570.72$$

$$I_{tot} = 4.78 \text{ amperes}$$

This total current  $I_{tot}$  required on the pipeline is distributed over the four (04) rectifying stations. Each rectifier transformer station must be able to deliver  $I_{tot}/4$ , i.e., a current of  $I = 1195$  Milliampere per rectifying station.

### III.3.2. Calculating the number of anodes (Bed of anodes)

The anodic bed is intended to diffuse the protection current coming from the positive pole of a transformer-rectifier station into the ground. This current diffusion is carried out by the anodes which will be installed horizontally at the bottom of the trench and connected to a connecting cable. It must therefore be made of current-conducting materials. Behaving like an anode, it is subject to oxidation phenomena. The mass of the material constituting the anodic bed must be determined so that the installation has a lifespan of the order of 15 to 30 years.

The anode beds **FigureError! Reference source not found.** generally consist of:

- Anodes.
- A cable to connect the anodes.
- Bypass kits.
- Regulator mix: backfill.

The anodes will be buried in low-resistivity coke backfill.



Figure III-4: Anodes of type (fer-silicium-chrome).

The implantation of the anode bed will preferably be carried out in a zone of low resistivity. The anodes used will be in Ferro-Silicon alloy with added Chrome (Anode Fe/Si/Cr).

Table III-3: Dimensional characteristics of the anode

Anode type	Anode body		
	∅ (mm)	L (mm)	Net weight (kg)
2" x 60"	50.8	1524	22.7

The number of anodes is obtained from the following formula:

$$N = \frac{M_a}{m_a} \quad (3.7)$$

With:

**N**: Number of Anodes.

**M<sub>a</sub>**: Total Mass in Kg.

**m<sub>a</sub>**: Unit mass of anode in Kg.

To meet a current requirement of **1.195 Ampères**, the anode mass will be:

$$M_a = Ca. T. I \quad (3.8)$$

With:

**Ca:** Anode consummation in Kg/A.yr (0.5kg/A.yr for the following type Fe/Si/Cr).

**T:** Lifespan in years (25 years).

**I:** Current in amperes.

$$M_a = 0,5 \cdot 25 \cdot 1,195 = 14,94 \text{ kg}$$

So, from formula (3.7), the number of anodes will be:

$$N = 0.66, \text{ therefore: } 1 \text{ anode per ground bed.}$$

### III.3.3. Rectifier station power

The rectifier power is calculated using the following formula:

$$P = \frac{1}{\eta} \times R \times I^2 = \frac{1}{\eta} \times (R_T + R_A + R_C) \times I^2 \quad (3.9)$$

**R<sub>t</sub>:** Pipe resistance ( $\Omega/m$ ).

**R<sub>A</sub>:** Anodic bed resistance ( $\Omega/m$ ).

**R<sub>c</sub>:** Cable resistance ( $\Omega/m$ ).

**\* Pipe resistance **R<sub>T</sub>** Neglected**

**R<sub>A</sub>: Anodic bed resistance ( $\Omega/m$ ).**

The theoretical resistance of the bed of anodes makes it possible to provide the required current of **1.1975 ampères** under voltage less than the maximum rectifier voltage of **60 volts**.

The ground contact resistance of the anode bed is given by Dwight's formula:

$$R_A = \frac{\rho}{2\pi L} \left( \ln \frac{4L}{D_a} - 1 \right) \quad (3.10)$$

**R<sub>A</sub>:** Ground contact resistance in  $\Omega$ ;

**$\rho$ :** Ground resistivity in  $\Omega \cdot m$ ;

**L:** Length of the anode (To be checked or of the anode bed) in  $m$ ;

**D<sub>a</sub>:** Diameter of the anode in  $m$ .

The ground has a particular influence on the steel (Risk of corrosion) and the resistivity depends on the aggressiveness of the ground, the factors that influence the nature of the ground are:

- Chemical nature (composition)
- Humidity level
- Soil pH
- Granulometry
- Ventilation

The method used for resistivity measurements for the ground in Sonatrach pipes is the four probes called the WENNER method.

The measurement of soil resistivity is the sum of many aspects .. but we're going to work with the average resistivity value in the station of Haoud El Hamra (HEH) which is 60 Ω.m.

$$R_A = \frac{60}{2\pi \times 1.524} \left( \ln \frac{4 \times 1.524}{0.0508} - 1 \right) = 23.74 \Omega$$

$R_c$ : Cable resistance (Ω/m).

The cable used is of the U1000R02V type, made of copper conductor. the various existing links are summarized in **Table III-4** .

*Table III-4: Link cables*

Outlet type	Section (mm <sup>2</sup> )	Length (m)	Observation
<b>Anode's cable</b>	$S_{c1} = 1 \times 16$	$L_{c1} = 45m$	<b>3m per anode</b>
<b>Anode connecting cable</b>	$S_{c2} = 1 \times 25$	$L_{c2} = 80m$	
<b>Connecting cable to (+) terminal of rectifier transformer</b>	$S_{c3} = 1 \times 50$	$L_{c3} = 200m$	

$$R_c = \rho_c \times \frac{L_c}{S_c} = \rho_c \times \left( \frac{L_{c1}}{S_{c1}} + \frac{L_{c2}}{S_{c2}} + \frac{L_{c3}}{S_{c3}} \right) \tag{3.11}$$

$\rho_c$  : Cable resistivity (Ω.m).

$$R_c = 1.72 \cdot 10^{-2} \times \left( \frac{45}{16} + \frac{80}{25} + \frac{200}{50} \right) = 0.172 \Omega$$

So  $R = 23.91 \Omega$  ..... therefor our rectifier power  $P$  is 10674.10 watt.

### III.4. Corrosion detection and inspection methods

Metal loss and crack detection are areas that require significant, intelligent tools.

Two techniques are specifically emphasized for detecting metal loss:

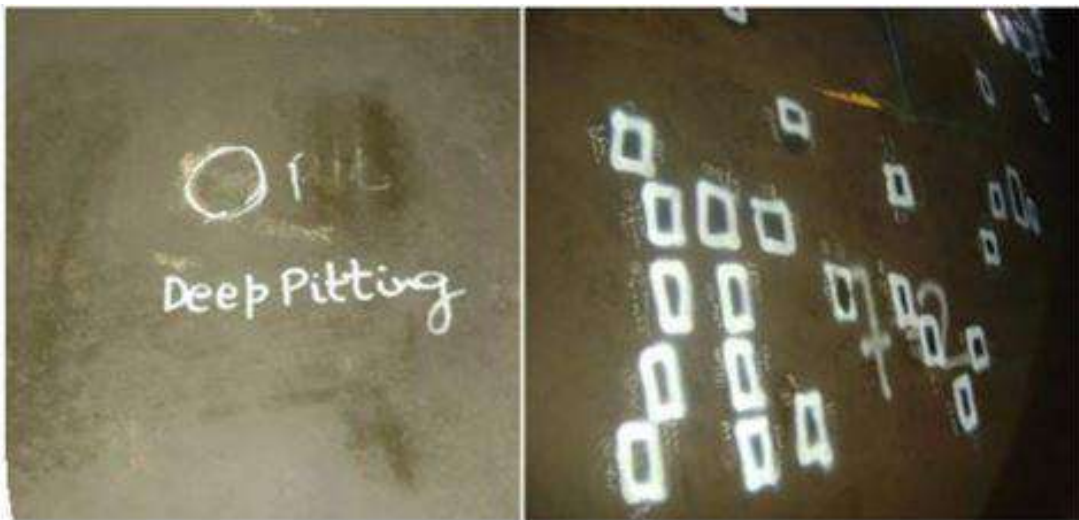
*a) Identifying thickness loss using non-destructive methods:*

- ✓ Magnetic flux leakage (MFL) detection.
- ✓ Detection by visual inspection or UT ultrasound (ultrasonic technique).

*b) Measurement of mass loss through laboratory testing.*

#### III.4.1. Visual control

This particular inspection method is employed to assess the condition of the pipe and visually inspect for any signs of metal surface corrosion, as shown in **Figure III-5**. This initial inspection typically only identifies significant defects that are visible to the naked eye, such as excessive deformation (clear indication of the loss of original geometry) and a reduction in pipe thickness.



*Figure III-5: Visual control of corrosion*

#### III.4.2. Inline Inspection with Magnetic Flux Leakage (MFL)

This technique employs the use of potent magnets to induce a magnetic flux within the walls of a pipeline. Positioned between the magnetic poles, sensors are utilized to detect any alterations in intensity that may arise from the loss of metal or changes in thickness. Notably, the magnetic flux power required for this method is relatively high. Initially, the initial MFL tools encountered challenges due to this drawback, particularly concerning large pipe diameters. Nevertheless, the application of an intelligent tool (MFL) for inline inspection can furnish almost all the necessary information for reassessing the technical condition of a pipeline.



However, the responsibility for determining the appropriate rehabilitation strategies and maintenance practices to preserve the structural integrity falls upon the operator. With many of the world's pipelines having surpassed their operational lifespan, yet still maintaining functionality, regular monitoring of their technical condition and the implementation of a suitable maintenance policy are imperative. In such cases, the pivotal query revolves around whether to pursue repair or rehabilitation. Addressing this question entails an exhaustive inspection program to procure the requisite data for evaluating the condition of the pipeline. This study aims to ascertain the feasibility of employing the intelligent tool within the pipeline.

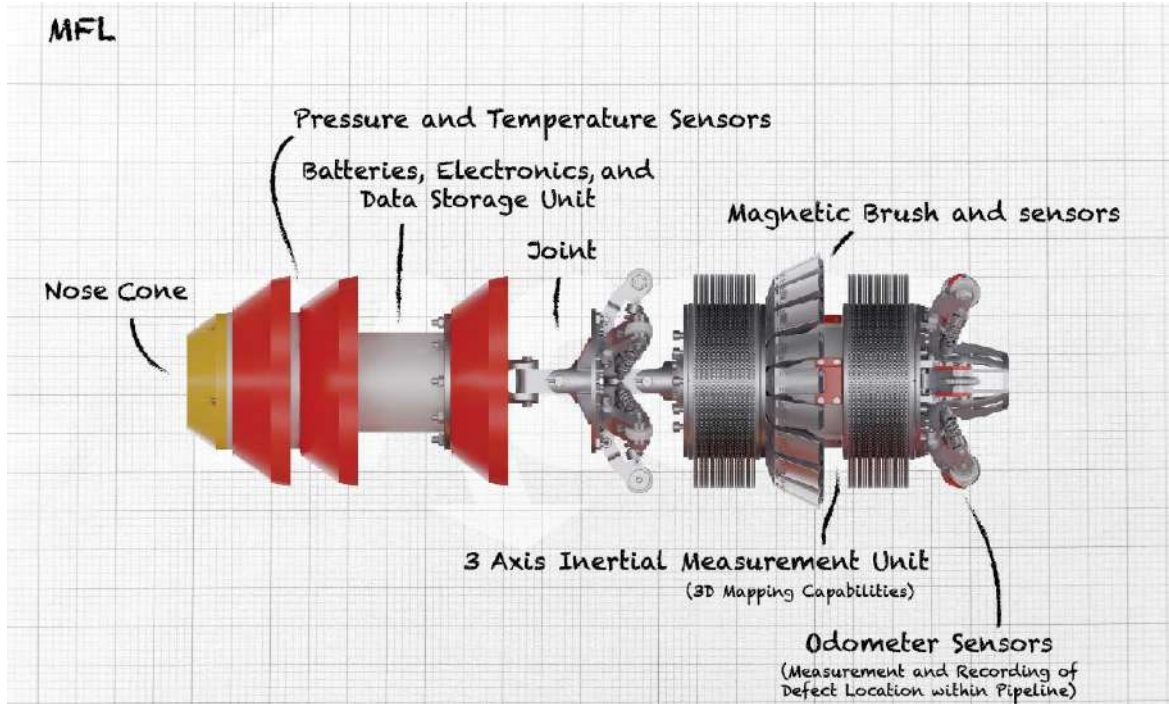


Figure III-6:MFL

Planning an inspection generally involves three steps:

- Pipe cleaning with conventional tools Figure “PIC A”.
- Sending the geometry tool to detect possible blockages “PIC B”.
- Sending the intelligent tool for locating metal losses and assessing their significance “PIC C”.



### III.4.3. Ultrasonic detection and inspection

The principle of ultrasonic non-destructive testing (also known as ultrasound testing) consists in emitting an ultrasonic wave that propagates through the part to be inspected and is reflected in the obstacles it encounters (anomalies, part boundaries).

ultrasonic non-destructive testing:

- detect internal defects in various materials.
- perform thickness measurements on coatings.
- check equipment without dismantling.
- measure internal or external corrosion.
- perform adhesion and delamination checks.
- check the conformity of welds, forging and casting parts, ceramics, etc.

Ultrasound testing is quick to perform and provides immediate results. The use of ECHOGEL ultrasound gel during non-destructive testing will optimize reading and inspection.



*Figure III-7: ultrasonic thickness measurements device*

### III.4.4. Long Range Ultrasonic Testing (LRUT)

#### III.4.4.1 Principle

LRUT (Long Range Ultrasonic Testing) is an advanced non-destructive examination technique specifically designed for testing large volumes of material from a single test point. What sets it apart from more traditional ultrasound methods is that it doesn't require a liquid coupling between the transducers and the surface. This unique feature makes LRUT one of the fastest inspection tools available for monitoring corrosion and other types of damage in pipelines.



Its applications in pipeline inspection are diverse, including areas such as road and river crossings, power station tubes, risers, surface pipelines, jetty lines, and refinery pipelines. It excels at detecting problems like corrosion under insulation. Moreover, LRUT is particularly useful in situations where other detection methods are not feasible, such as buried pipes, pipes enclosed in a sleeve, or pipes located at high altitudes. It is especially well-suited for the following applications:

- Screening insulated pipes for external and internal corrosion without removing insulation.
- Screening of pipes passing through the dike wall.
- Screening of crossing pipes on:
  - river
  - lines
  - piers.



*Figure III-8:LRUT in action*

LRUT is conducted using a system comprised of several components: a low-frequency flow detector, a pulse receiver, a set of transducer rings, and a laptop equipped with controlling software, as shown in **Figure III-8**. The initial step involves positioning the transducer rings around a pipe, which will serve as the source for generating a series of low-frequency guided waves. The key aspect is the even distribution of ultrasonic transducers along the circumference

of the pipe, enabling the guided waves to propagate uniformly along the pipe's axis. This ensures comprehensive and complete coverage of the pipe wall, including areas near collars and pipes that are sheathed or buried. As the waves encounter a change in wall thickness, they are reflected back to the transducer, enabling the detection of corrosion, metal loss, or any irregularities in the process.

### III.4.4.2 Analyzing the results

The result of each test site is presented on a report sheet similar to the one presented below:

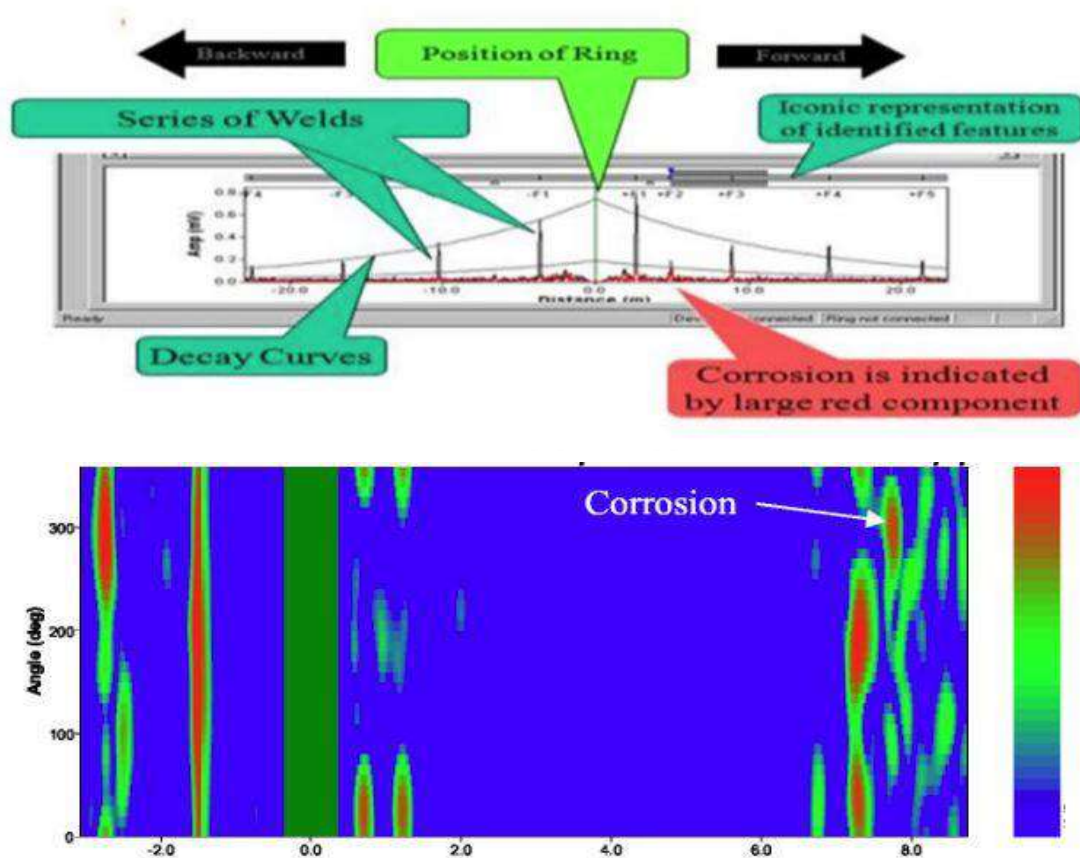


Figure III-9: Result reading by LRUT method.

### III.4.4.3 Classification rule

#### b) Classification Rule 1: (Severe Corrosion)

In this classification, prominent and thick black or red lines are observed both above and under the CAD call point. These lines suggest the presence of severe corrosion in the material. The corrosion damage is extensive and may significantly compromise the structural integrity or functionality of the material.

#### c) Classification Rule 2: (Mild Corrosion)

This degree of corrosion is deemed acceptable when the black trace is positioned between the CAD call point and the Welding CAD, while the red trace remains below that of the CAD call

point. It should correspond to a reduction of over 10% in the distributed cross-section, without constituting a complete through-wall defect. This type of corrosion is visually represented as a blue exclamation mark (!) in the generated results.

*d) Classification Rule 3: (Minor corrosion)*

This corrosion level is considered satisfactory when both the black trace (symmetrical) and the red trace (non-symmetric) are situated below the CAD call point. It should correspond to a corrosion condition where the loss of cross-sectional area is less than 10%. These indications commonly signify that the pipes are in generally good condition. In the generated results, this corrosion level is depicted as a black dot (!).

**III.4.4.1 General rules**

Figure 15 shows an in-ground inspection of a large-diameter pipe crossing a road. The ring was positioned to inspect the buried, inaccessible part. The coupon used must be free of defects in order to allow successive measurements:

- A homogenous surface is required.
- The coupon's shape must be taken into account when positioning it in the fluid stream.
- It must be electrically insulated from its support.
- It must be degreased before use and protected during storage.
- Use plastic gloves when handling.
- 



*Figure III-10: Flexible ring for pipe inspection*

The coupons must be kept in a secure location with tight air pressure if they are not immediately used.

### **III.5. Cathodic protection potential measurement**

One of the key aspects of CP system monitoring and maintenance in Sonatrach is the measurement of potentials at various points on the structure. This procedure provides a detailed overview of the cathodic protection potential measurement method.

Measuring potential differences between close test stations is a common practice in cathodic protection. Test stations are strategically placed locations on a structure where potential measurements are taken to assess the effectiveness of the cathodic protection system.

This information helps identify potential variations or deficiencies in the system and allows for targeted adjustments or maintenance.

#### **III.5.1. Polarized potential measurement technique**

##### **III.5.1.1 Equipment Preparation**

- ✓ Gather the necessary equipment, including a high-impedance voltmeter, reference electrodes (such as Cu/CuSO<sub>4</sub>), and appropriate test leads and cables.
- ✓ Verify that the voltmeter is calibrated and functioning correctly.
- ✓ Ensure the reference electrodes are in good condition and securely attached to the structure at the desired measurement locations.

##### **III.5.1.2 Test station Selection**

- ✓ Identify the specific test station on the structure where potential measurements will be taken.
- ✓ Consider factors such as coating condition, proximity to anodes, and areas prone to corrosion or known deficiencies.

##### **III.5.1.3 Potential reading**

- ✓ Clean the surface area around the test point using a wire brush or similar cleaning tool to ensure good electrical contact.
- ✓ Connect the test leads from the reference electrode to the appropriate terminals on the voltmeter. Confirm that all connections are tight and that there are no loose or damaged cables.
- ✓ Turn on the voltmeter and set it to the appropriate measurement range.
- ✓ Read the potential value appearing on the voltmeter screen and check that it is stable.  
To note
- ✓ the potential appearing on the voltmeter screen, as well as its polarity (+ or -). Be sure to record both values of potential, ON and Instant OFF
- ✓ Take the potential reading displayed on the voltmeter and record it.

#### **III.5.1.4 Documentation**

- ✓ Maintain accurate records of all potential measurements, including the measurement locations, dates, and times.
- ✓ Keep a logbook or electronic database to track the potential measurements over time and monitor the system's performance.
- ✓ Document any actions taken or recommendations for future reference, compliance, and reporting purposes.

#### **III.5.1.5 Data Interpretation**

Interpreting the results of cathodic protection potential measurements involves comparing the measured potentials with industry standards, assessing polarized and depolarized potentials, examining potential gradients, and considering historical data and the corrosion environment. It is important to identify signs of effective protection, potential corrosion concerns, overprotection issues, and areas requiring attention. Consulting corrosion professionals and experts can provide valuable guidance during result interpretation. Overall, the interpretation helps determine the performance of the cathodic protection system and informs necessary actions for maintaining corrosion control and structural integrity.

#### **III.5.2. Depolarization measurements technique**

The depolarization reading method allows for the determination of the pipe's so-called "static" potential, i.e., without the impact of the cathodic protection system.

Potential measurements, like potential readings in an interruption cycle, are taken at regular intervals along the pipeline (typically one measurement every 10 meters). To enable for a meaningful comparison, measurements taken in depolarization mode must exactly correspond to measurements taken in cyclic mode.

The intervention thus consists of performing potential measurements in near space in depolarization mode, which must include the following steps:

- ✓ Preparation for the intervention.
- ✓ Preparation for depolarization Potential measurements
- ✓ Post-intervention restoration of current rectifiers.

#### **III.5.3. Taking measurements at the verification point**

Measurements at verification points must be carried out according to the following steps:

Identify the verification point to be assessed:

- Draw a diagram of the cables and their connections.
- Connect the copper sulfate reference electrode to the negative terminal of the voltmeter
- Connect the positive terminal (usually red) of the voltmeter to the cable of the negative contact of the structure to be tested.
- Read the potential value on the voltmeter display and check its stability. Record the potential shown on the voltmeter display, and its polarity (+ or -). In the case of a voltmeter with memory, save this value.
- If a second negative cable is present at the checkpoint, connect the positive terminal of the voltmeter to this cable.
- Read the value of the potential appearing on the voltmeter screen, ensure its stability and that it corresponds to the first value recorded, making it possible to ensure contact adequate negative
- Record the potential shown on the voltmeter display, and its polarity (+ or -). In the voltmeter, save this value in your memory.
- Repeat these measurements at each checkpoint.

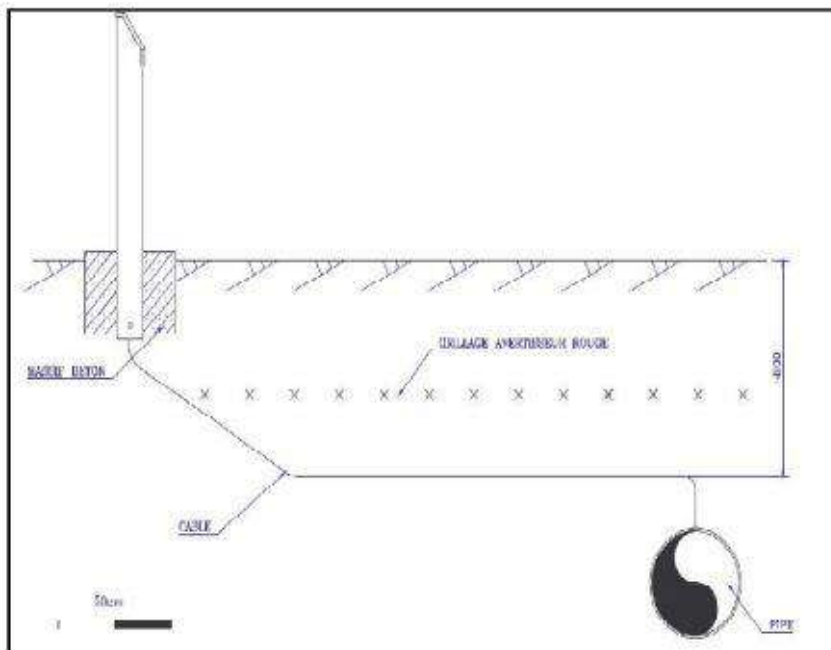


Figure III-11: Test point for potential measurement



### III.6. Equipment used in potential measurements and its defects

#### III.6.1.copper (II) sulfate electrode

The copper (II) sulfate reference electrode is a key component in potential measurement. It consists of a cylindrical plastic reservoir sealed by a porous plug. Inside the reservoir is a copper rod immersed in a saturated solution of copper sulfate. This electrode serves as a stable reference for potential measurements, ensuring accurate comparisons between electrochemical systems.

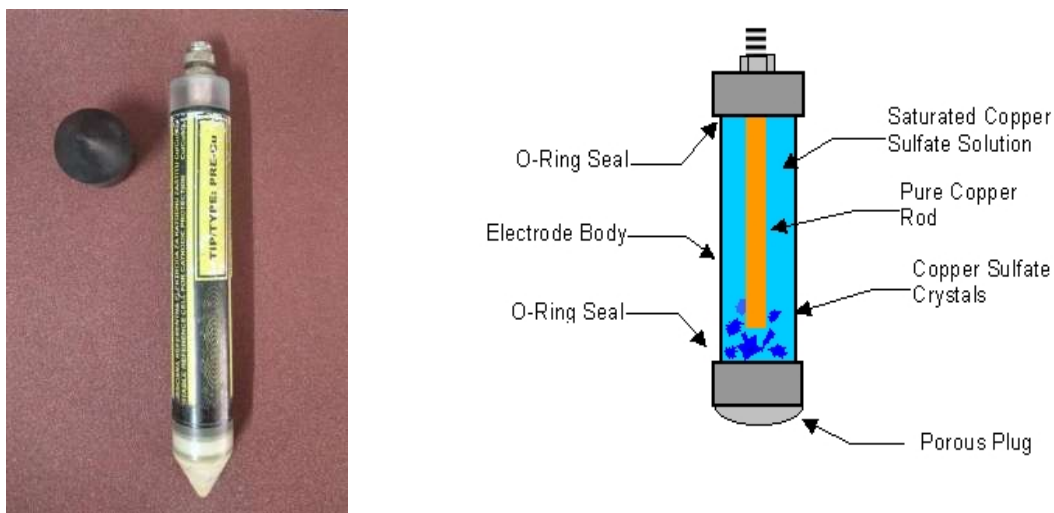


Figure III-12: Copper(II) sulfate electrode

##### III.6.1.1 The problem with copper (II) sulfate electrode

Technicians at Haoud El Hamra face the challenge of electrolyte leakage in reference electrodes. This problem occurs when the electrolyte solution, which plays a vital role in maintaining a stable potential and ensuring precise electrochemical measurements, unintentionally escapes from the electrodes. Various factors, including construction defects, aging, physical damage, and improper handling/storage, can contribute to this electrolyte leakage. As a result, the reliability and accuracy of electrochemical measurements are compromised, leading to inaccurate data and hindering effective analysis. In light of this issue, our study aims to propose a potential solution to address the leakage problem and restore the electrodes' functionality.

##### III.6.1.2 The suggested solution

The proposed solution to address the issue involves developing a conductive gel in the laboratory. This gel acts as a protective barrier when applied to the electrodes, effectively preventing the unintentional escape of the electrolyte solution. By implementing this solution, the integrity of the electrodes can be maintained, ensuring accurate electrochemical measurements and addressing the issue of electrolyte leakage.

### III.6.2. Laboratory experiment

In this experiment, we will synthesize a conductive gel out of three primary ingredients: polyvinyl alcohol (PVA), copper sulfate, and distilled water. A water-soluble polymer, polyvinyl alcohol, functions as a gel matrix, preserving structural integrity and preventing the gel from leaking out of the reference electrode. Copper sulfate acts as a conductive component in the gel, permitting ion mobility. Distilled water serves as a solvent, guaranteeing homogeneity and promoting ion mobility.

➤ **Laboratory equipment:**

Balance, watch glass, Erlenmeyer flask, graduated cylinder, burette, PH meter, magnetic stirring crystallizer, funnel.

➤ **Chemical reagents:**

Polyvinyl alcohol (PVA), Copper (II) sulfate pent hydrate ( $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ ), Distilled water



Figure III-13: Polyvinyl alcohol (PVA), Copper (II) sulfate pent hydrate ( $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ ).

➤ **Procedure**

- a) To begin, measure the specified quantity of  $\text{CuSO}_4$  indicated in the table provided (below). Combine this amount with 50 mL of distilled water. Transfer the water into a heat-resistant glass or plastic container, and heat it using a hot plate or another suitable heat source until it reaches a temperature of  $80^\circ\text{C}$ . This elevated temperature will aid in the easier dissolution of PVA.





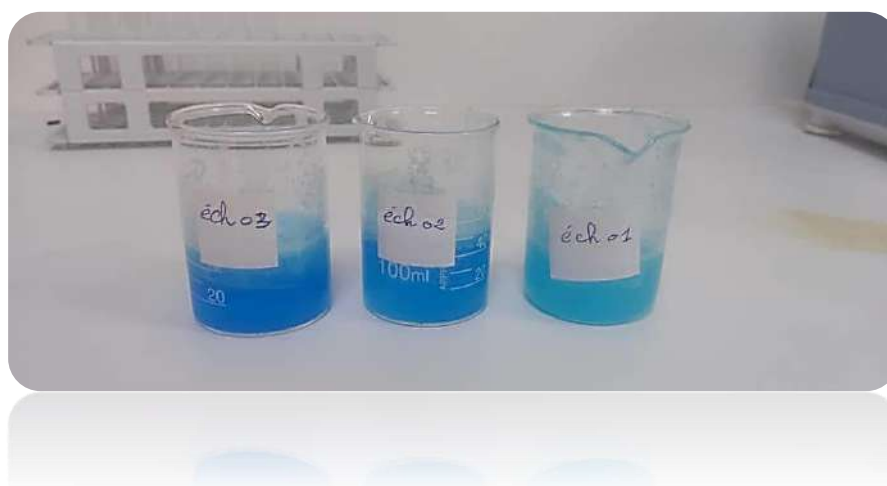
- b) After achieving a temperature of 80°C for the water, begin adding the PVA to the container while stirring continuously. Continue stirring until the PVA is completely dissolved in the water. This may take several minutes, depending on the particle size of the PVA and the stirring speed. Once the PVA is completely dissolved, the resulting solution should be transparent, while the presence of  $\text{CuSO}_4$  will impart a dark blue color to the solution.



- c) Keep heating and stirring the mixture until both the PVA and copper sulfate have fully dissolved, ensuring that the solution becomes homogeneous. The duration of this process can vary depending on factors such as the particle size of the PVA and the concentration of copper (II) sulfate. Once the solution is completely homogeneous, stop heating it and allow it to cool.

### III.6.3. Result and Analysis

During the cooling process, the solution will undergo a transformation, thickening gradually until it solidifies into a gel-like state. The time required for this transition can vary depending on factors such as the size of the container and the room temperature. Once the gel has formed, it should appear as a clear and homogeneous mass.



The resulting gel contains copper (II) sulfate dissolved within a PVA matrix, creating a stable and conductive medium suitable for electrochemical applications.

\*It's worth noting that the experiment was conducted three times, with each iteration involving a modification in the quantities of both copper (II) sulfate and PVA used.

The following table shows the characteristics and measurements of each sample:

*Table III-5: Experiment results*

Sample	(1)	(2)	(3)	(4)
$V_{CuSO_4}$ (ml)	50	50	50	50
$m_{CuSO_4}$ (g)	2.5	2.5	4.99	7.49
$m_{pva}$ (g)	/	5	5	5
$C_{CuSO_4}$ (mol)	0.5	0.2	0.4	0.6
$T$ (C)	13	80	80	80
<b>Conductivity</b> (g/l)	82.7	38.6	46.9	62.1

### III.6.4. Conclusion

Finally, the experiment sought to create a conductive gel that may serve as a viable alternative for the liquid electrolyte in a copper sulfate reference electrode. Three distinct samples were created using varied amounts of  $CuSO_4$ . While the gel's conductivity did not match that of the liquid electrolyte, the results were encouraging.

The next step is to calibrate the electrode reference so that we can get a stable potential out of it. We can do this by saturating the copper sulfate solution, which keeps the concentration of copper ions constant and contributes to the stability of the reference electrode's potential.

Maintaining a constant concentration of copper ions is critical for the copper/copper sulfate reference electrode's stable and consistent performance. It aids in the reduction of potential variations over time, providing a consistent reference point for electrochemical experiments.

Overall, the findings indicate that further optimization and modification of the gel composition may be necessary to close the quality gap.

## **Overall conclusion:**

In conclusion, this thesis has provided a comprehensive overview of cathodic protection systems, corrosion detection, and inspection methods. The study's findings shed light on key parameters, such as the number of rectifiers, anodes, soil resistivity, and the use of advanced techniques like MFL tools and ultrasound devices.

The study also emphasizes the importance of accurate potential measurements in evaluating cathodic protection systems. The procedures and equipment involved are discussed, and a new experiment is proposed that transforms liquid electrolyte into a conductive gel as a potential solution for addressing leakage issues.

These insights contribute to Sonatrach's ongoing efforts to optimize cathodic protection systems and reduce corrosion-related costs. The practical implications extend beyond academia, providing a foundation for developing and implementing effective strategies to combat corrosion and ensure the long-term integrity of critical infrastructure.

Future research can build upon these findings to further explore the potential of conductive electrolyte gels as an innovative solution to mitigate challenges associated with liquid electrolyte leakage.

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# ANNEX

ANNEX TABLE :

<b>ANNEX</b>	<b>Description</b>
<b>ANNEX 1</b>	The document provides a comprehensive details of cathodic protection potential measurements in both the "on" and "off" states, outlining procedures, standards, and recorded data for evaluating corrosion protection effectiveness.
<b>ANNEX 2</b>	The objective of this report is to take thickness measurements at the station's facilities.
<b>ANNEX 3</b>	A blueprint for constructing a permanent reference electrode.
<b>ANNEX 4</b>	A blueprint for building a test point.
<b>ANNEX 5</b>	A blueprint for welding connection cables
<b>ANNEX 6</b>	A plan for digging and inserting an anodic bed in the ground
<b>ANNEX 7</b>	synoptic diagram of cathodic protection for gas pipelines

# ANNEX: 1



Campagne de mesure ON canalisation OH4 - 30"

mars-21

## RELEVÉ DES POTENTIELS "ON" :

Prise	TYPE	Potentiel ON conduite SOL Cu/So4 (-V)	Observations
PK(Km)			
0,000	J1		Point de soutirage : I=270 mA HBNS
0,050	PG		Vg = - 0,34 V
0,250	PA		Piste inaccessible, ensablée
2+000	PCTE		Vcroisement Inj OH3 à l'arrêt (centrale électrique)
3,347	PP		Ligne HT
5,474	PP		Ligne HT
7,601	PA		Ligne HT
9,728	PA		Dune de sable Ligne HT
11,855	PP		Dune de sable Ligne HT
13,982	PP		Dune de sable Ligne HT
15,000	PA		
18,267	PP		
20,364	PP		
22,491	PA		
24,618	PP		
26,745	PP		
28,872	PA		
31,180	PCTE		VDP = - 4,2 V Résistance branchée
33,000	PP		
35,000	PP		
37,000	PA		
39,000	PP		Dune de sable
41,000	PP		Dune de sable
43,000	PP		Dune de sable
45,000	PP		Dune de sable
47,000	PA		Dune de sable
49,000	PP		Dune de sable
51,000	PP		Dune de sable
53,000	PP		Dune de sable
55,000	PA		Dune de sable
57,000	PP		Dune de sable
59,000	PP		Dune de sable
61,000	PP		Dune de sable
62,981	PA		PS2 ensablé et barodage sacagé
65,214	PP		Piste inaccessible, ensablée.
67,428	PP		Piste inaccessible, ensablée.
69,642	PP		Dune de sable
71,556	PA		Piste inaccessible, ensablée.
74,070	PP		Piste inaccessible, ensablée.
76,285	PP		Piste inaccessible, ensablée.
78,500	PA		Piste inaccessible, ensablée.
80,714	PA		Piste inaccessible, ensablée.
82,928	PP		Piste inaccessible, ensablée.
85,142	PP		Piste inaccessible, ensablée.
87,356	PA		Piste inaccessible, ensablée.

HEH, le : 12/04/2022

## PV DE MESURE DES EPAISSEURS

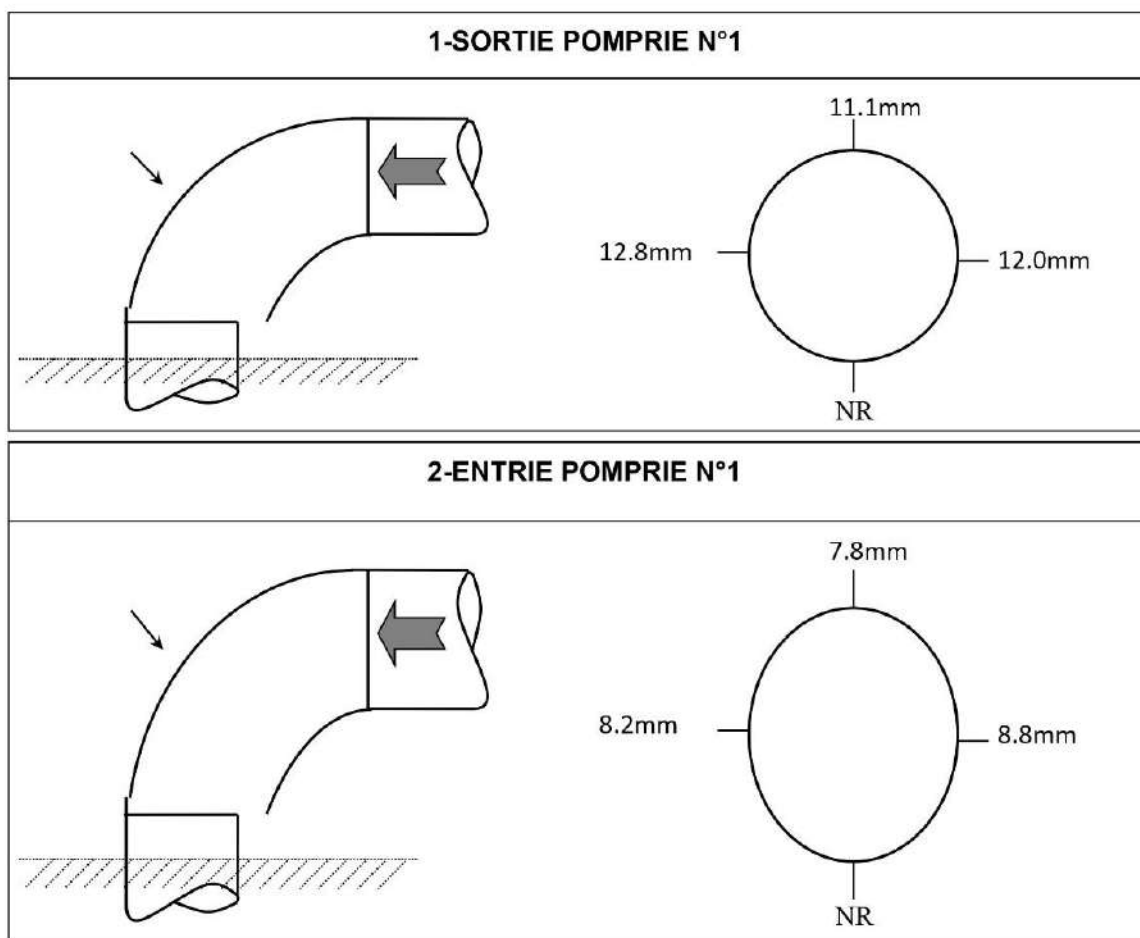
Ouvrage : Terminal Départ SP3(OZ2).

L'objectif de cette mission est de prendre des mesures d'épaisseur au niveau des installations de la station SP3(OZ2). Les points de mesure des épaisseurs sont choisis en présence des représentants de cette station.

L'appareil utilisé dans ce travail est :

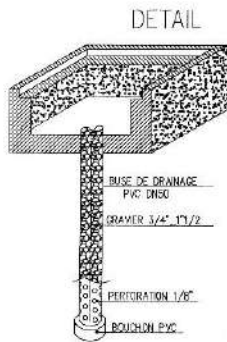
Mesureur d'épaisseur ELECOMETER serial No : TB 19732

Les figures suivantes illustrent les valeurs mesurées d'après le sens horaire de la canalisation :





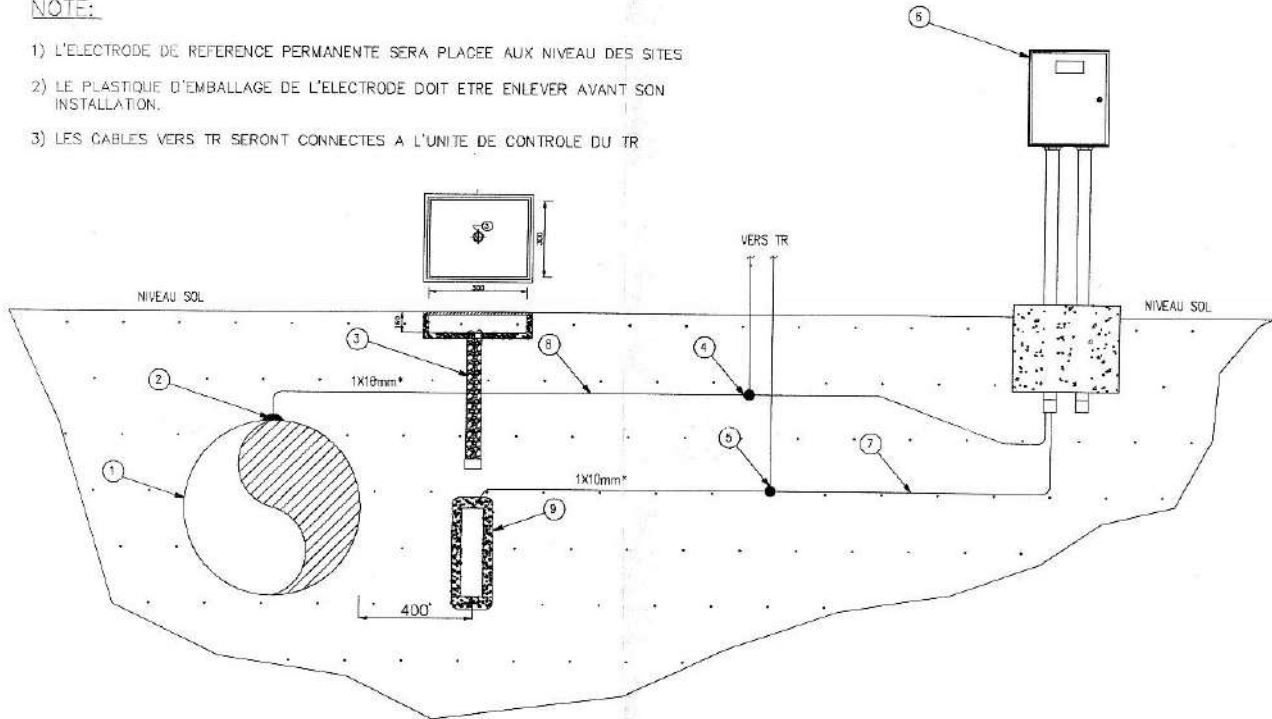
# ANNEX : 3






LEGENDE	
ITEM	MATERIEL
1	CONDUITE A PROTEGER
2	SOUDURE ALUMINOTHERMIQUE
3	TUBE D'ARROSAGE EN PVC REMPLIS DE GRAVIER ROND
4	JONCTION ENTRE CABLE 1x16mm *
5	JONCTION ENTRE CABLE 1x10mm *
6	COFFRET TYPE GSC
7	CABLE 1x10mm *
8	CABLE 1x16mm *
9	ELECTRODE DE REFERENCE PERMANENTE PRE-EMBALEE
10	REGARD D'ARROSAGE 300X300 X150 (VOIR DETAIL)

**NOTE:**

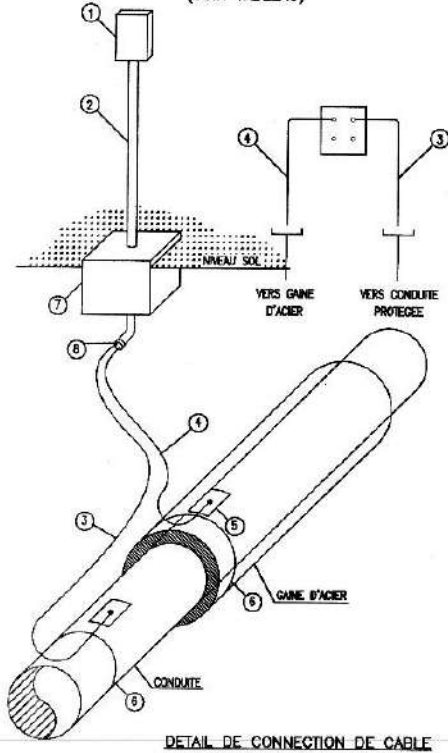
- 1) L'ELECTRODE DE REFERENCE PERMANENTE SERA PLACEE AUX NIVEAU DES SITES
- 2) LE PLASTIQUE D'EMBALLAGE DE L'ELECTRODE DOIT ETRE ENLEVER AVANT SON INSTALLATION.
- 3) LES CABLES VERS TR SERONT CONNECTES A L'UNITE DE CONTROLE DU TR



D	24/11/2015		A.B	G.R	
		POUR APPROBATION			
REV.	DATE	EDITIONS SUCCESSIVES	DESSINE	VERIFIE	APPROUVE
 		Division etudes et Developpement Direction Execution des Projets PROJET GAZODUC GR6 /Ø48" LOT 02 HASSI MESSAOUD-HASSI R'MEL			
TITRE DE PLAN		INSTALLATION D'UNE ELECTRODE DE REFERENCE PERMANENTE			
EHELLE		N° DE PLAN :			
Neant		GR6-000-PC-PL-008		REV:D	

**ANNEX: 4**

**INSTALLATION DE PRISE PTG AVEC SOCLE EN BETON  
(VOIR TABLEAU)**






**TABLEAU**

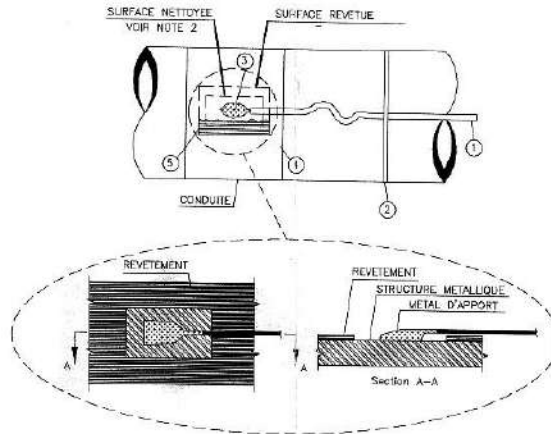
LISTE DU MATERIEL			
ITEM	QUANTITE	DIMENSIONS	DESCRIPTION
1	1	-	BOITIER
2	1	2"	CONDUIT POUR ENTREE DE CABLE
3	1	1x16 mm <sup>2</sup>	CABLE DE MESURE CONDUITE
4	1	1x25 mm <sup>2</sup>	CABLE DE MESURE GAINÉ
5	2	-	CONNECTION CABLE/CONDUITE
6	COMME REQUIS	COMME REQUIS	RUBAN D'ATTACHE CABLE
7	1	-	SOCLE EN BETON
8	1	2"	BOUCHON

**BUT:**

- 1) LE TYPE DE PRISE PTG DOIT ETRE INSTALLE A CHAQUE PASSAGE DE LA CONDUITE SOUS GAINÉ D'ACIER.
- 2) SI LA LONGUEUR DE LA GAINÉ D'ACIER EST SUPERIEUR A 10m, (02) DEUX PRISES TYPE PTG SERONT INSTALLEES EN AMONT ET AVAL DE LA TRAVERSEE DE ROUTE OU VOIE FERREE.
- 3) TOUTE LES CONNECTIONS CABLES-CONDUITES SERONT REALISES PAR SOUDURE ALUMINOTHERMIQUE.
- 4) LA PRISE PTG SERA INSTALLEE A 2m DU PIPE

D	24/11/2015		A.B	G.R
POUR APPROBATION				
REV.	DATE	EDITIONS SUCCESSIVES	DESSINE	VERIFIE APPROUVE
 		Division etudes et Developpement Direction Execution des Projets PROJET GAZODUC GR6 /Ø48" LOT 02 HASSI MESSAOUD-HASSI R'MEL		
TITRE DE PLAN		PRISE TUBE / GAINÉ TYPE PTG		
ECHELLE Neant		N° DE PLAN : GR6-000-PC-PL-003		REV:D

ANNEX: 5






SOUDEAGE ALUMINOTHERMIQUE DETAIL 1

TABEAU

LISTE DU MATERIEL				
ITEM	QUANTITE	DIMENSION	DESCRIPTION	NOTE
1	COMME REQUIS	COMME REQUIS	CABLE DE PROTECTION CATHODIQUE	-
2	COMME REQUIS	COMME REQUIS	RUBAN D'ATACHE CABLE	-
3	COMME REQUIS	COMME REQUIS	COSSE DE CABLE	-
4	COMME REQUIS	COMME REQUIS	BANDE PLASTIQUE AUTOUR DU PIPE	-
5	COMME REQUIS	COMME REQUIS	BOITE EN PLASTIQUE	-
6	COMME REQUIS	-	BARRETTE DE LIAISON CUIVRE	-

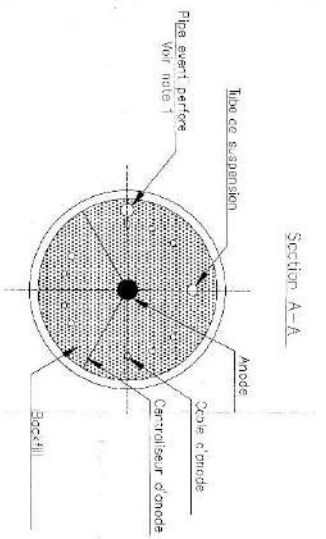
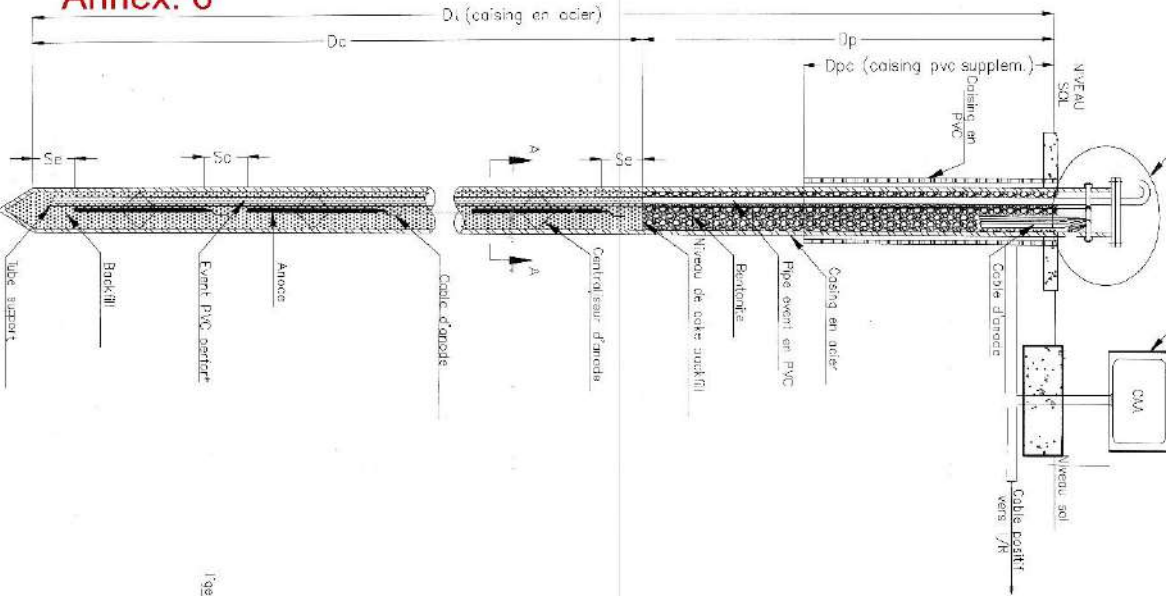
NOTE:

- 1) Toutes les traces d'huile, graisse et autre contaminant existant sur la surface du metal ou le revetement doit être enlevées avant ponçage ou remplissage.
- 2) Le revetement doit être enlevé sur une surface approximative de 50x50mm en utilisant une meule ou équivalent. La surface doit ensuite être nettoyée avec une brosse métallique des précautions doivent être prises afin de ne pas compromettre l'épaisseur du métal de base, durant l'opération de nettoyage.
- 3) Le soudage aluminothermique (CADWELD) doit être pris en charge par l'entrepreneur en utilisant les procédures préalablement approuvées et par un opérateur qualifié.
- 4) La connection doit être mécaniquement testée en tapant dessus avec un marteau à caoutchouc solide.
- 5) La connection du câble doit être testée par arrachage dans la direction de pose.
- 6) Le soudage Aluminothermique detail 2 est spécifique pour la connection de câble négatif de dimensions 1x50 mm<sup>2</sup>, 1x35mm<sup>2</sup>.
- 7) La couverture de la soudure par mastic à deux composants et finition par bande plastique thermo-retractable.

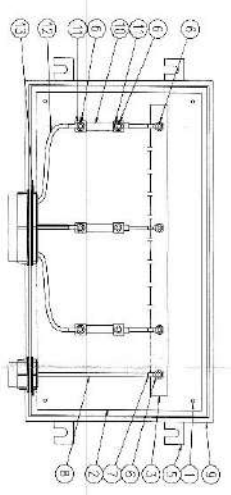
D	24/11/2015			A.B	G.R	
POUR APPROBATION						
REV.	DATE	EDITIONS SUCCESSIVES		DESSINE	VERIFIE	APPROUVE
 		Division études et Développement Direction Execution des Projets PROJET GAZODUC GR6 /Ø48" LOT 02 HASSI MESSAOUD-HASSI R'MEL			 T.R.C	
TITRE DE PLAN		PRISE DE CONECTION CABLE- CONDUITE				
ECHELLE		N° DE PLAN :				
Neant		GR6-000-PC-PL-007			REV:D	



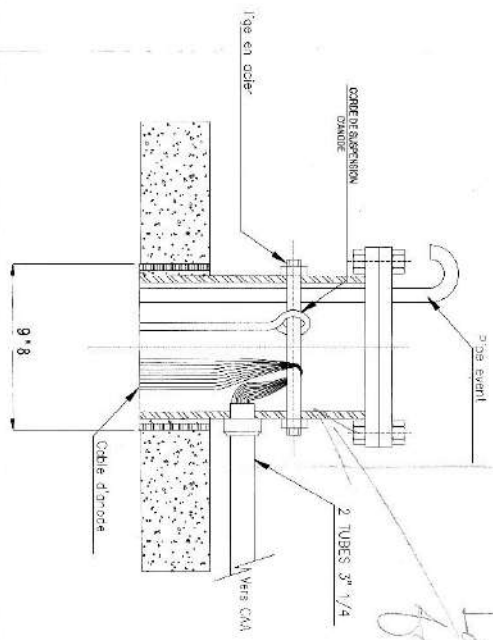
# Annex: 6



Détail 1 - Coffres et d'alimentation d'anodes (CAAP)



Détail 2 - Terre de puit



*La fixation des anodes doit se faire avec un tube galvanisé (Pas de câbles en acier, la fixation)!*

*Remarque de Christophe*

- 4) UN TUBE EN ACIER GALVANISÉ SERA INSTALLÉ A L'INTÉRIEUR DU CAISNING EN ACIER POUR LA SUSPENSION DES ANODES
- 5) LA TIGE DOIT ÊTRE FILTRÉE DANS LES DEUX EXTRÉMITÉS
- 6) LA LONGUEUR INACTIVE DOIT ÊTRE RÉGULIÈREMENT MESURÉE, MAIS QUE LA PARTIE ACTIVE SERA REMPLIE DE BACKFILL
- 7) UN GÉNÉRATEUR PNEU MATRIÉ SERA MONTÉ ET UTILISÉ
- 8) LE BAS DU CAISNING DOIT ÊTRE ESSAYÉ
- 9) LA LONGUEUR INACTIVE DOIT ÊTRE RÉGULIÈREMENT MESURÉE, MAIS QUE LA PARTIE ACTIVE SERA REMPLIE DE BACKFILL

TABLEAU DES DIMENSIONS POUR DIVERSES

SITE	PK	PKC D'ANODE	RENDEMENT PROBABILISTE (AN)	RENDEMENT ACTIF (AN)	RENDEMENT INACTIF (AN)	RENDEMENT TOTAL (AN)
RS n°11	284475	14-9-C	12	250	110	35
RS n°13	285100	14-9-C	12	250	110	35
RS n°19	317446	14-9-C	12	250	110	35
RS n°18	412888	14-9-C	12	250	110	35
RS n°20	474443	14-9-C	12	250	110	35
RS n°22	551481	14-9-C	12	250	110	35

- 1) LISTE DU VA-T-EN-LE POUR COFFRE CAAP
- 2) UN DE PASSE
- 3) ÉCROU EN DROIT
- 4) ÉCROU EN DROIT
- 5) ÉCROU POUR FIXATION EXTÉRIEURE
- 6) ÉCROU EN DROIT ET TROUSILLE
- 7) ÉCROU EN DROIT AVEC TROUS DE TRAVERS
- 8) CÂBLE POSTER 3/8" 1/4"
- 9) CÂBLE EN ACIER
- 10) MESSURAGE RÉGULIÈRE
- 11) ÉCROU ET CÂBLE AVEC TROUS DE FIXATION
- 12) CÂBLE ÉCROU

TOUR D'OPÉRATION

DATE

ÉCHÉLLE

TYPE DE PLAN

PROTECTION CATHODIQUE DÉFINITIVE

PROJETANT

REVISÉ

DATE

PROJETANT

REVISÉ

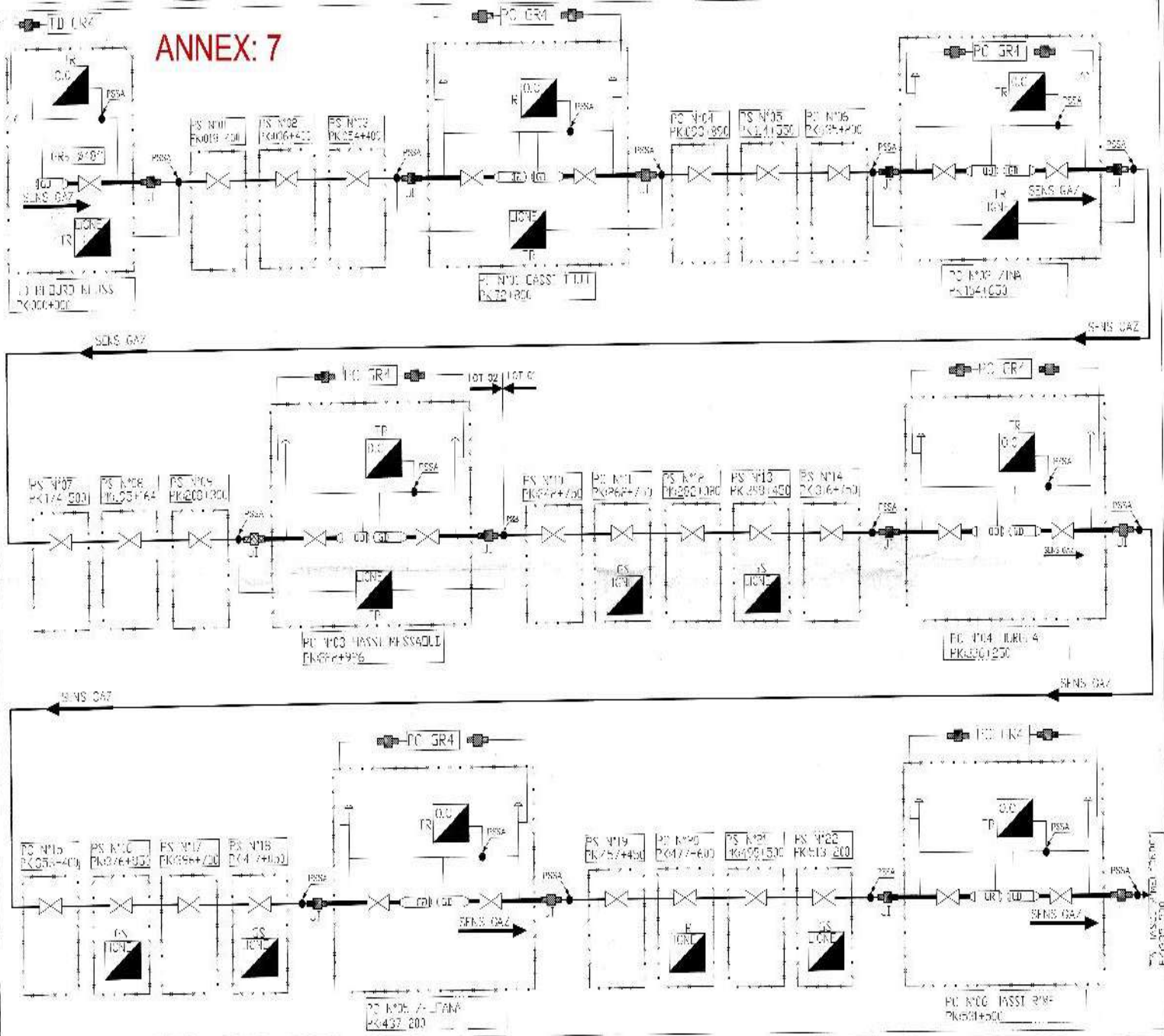
DATE

PROJETANT

REVISÉ

DATE

# ANNEX: 7



REF: PC  
 TR: TRANSFORMATEUR  
 GND: GROUND  
 PS: POTENTIAL STATION  
 PC: POWER SOURCE

SCHEMA SYNOPTIQUE DE LA PROTECTION CATHODIQUE GAZODUC GR6048" DU PK:0+000(TD)AU PK: 535+500(CNDG)