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Corrosion Control By Cathodic Protection For Low Carbon Steel Pipeline in Salt Solutions

A Thesis

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By

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بسم الله الرحمن الرحيم

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صدق الله العلي العظيم

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Ghofran Abdalkareem

Abstract

The study was carried out by conducting the design of a cathodic protection system using the applied current method to protect a carbon steel tube in order to study the different factors that affect the applied current that would protect all or part of the tubular metal sample (cathode) using a graphite electrode as an anode.

Use weight as a performance indicator for the cathodic protection procedure. Three main variables that have a significant impact on the cathodic protection process were tested to ensure its performance.

The applied current is tested, using three values of voltage less than the protection voltage equal to -0.85v,-0.65v in a salt medium with variable concentrations of 5, 10 and 20.35 g/L NaCl and for different distances between the cathode and the anode of 2, 25 and 50 cm and different temperatures of 20, 30 and 40 ℃.

The results showed that (E potential) is more negative with increasing salt concentration, temperature and distance between electrodes. Also, the cathodic protection current density increases with increasing salt concentration, temperature and distance between electrodes. The corrosion rate then increased with increasing salt concentration and temperature.

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Nomenclature

Symbol	Meaning	Unit
C	Nacl Concentration	g/L
CR	Corrosion Rate	Mpy
A	Surface Area of Cathode	m^2
$E_\circ$	Equilibrium Potential	V
D	Diffusion Coefficient of Reaction ion	m^2/s
F	Faraday Constant (96500)	Coulomb/equiv
i	Current Density	mA/cm^2
ICCP	Impressed Current Cathodic Protection	-
Ic	Cathodic Current Density	mA/cm^2
I_{cp}	Cathodic protection Current Density	mA/cm^2
L	Tube metal specimen length	Cm
n, z	Number of electrons transferred	-
R	Resistance	Ω
SCE	Saturated calomel Electrode	V
t	Exposure time	Sec
T	Temperature	˚C

D	Distance between cathode and anode	Cm
Δ w	Weight loss	G
Od	Outside diameter	Cm
MT	Molecular weight of metal	g/mol
mm/y	Millimeter penetration per year	-
Mpy	Millinch penetration per year	-
Δ g	Gibbs free energy change	kj/mol
P	Resistivity	mΩ. Cm
Δ	Thickness of the diffusion layer	CM
A	Symmetry Factor = 0.5	
Opc	Open-Circuit Potentials	

CHAPTER ONE

Introduction

1.1 Background

A majority often used corrosion definition is the demolition of a substance as a result of a chemical interaction between the material and its surroundings. Usually, this destruction manifests itself as material disintegration or redeposition in other forms on the surface of the object. The most common building materials are metallic systems, which are inherently prone to corrosion. Therefore, the majority of corrosion research concentrates on metals and alloys [1,2].

The problem of corrosion continues to be of great concern to companies all over the world despite significant advancements in corrosion research and technology. Although the harmful effects of corrosion may be greatly reduced by choosing materials that are extremely resistant to corrosion, the expense involved with doing so encourages the use of inexpensive metallic materials coupled with effective corrosion prevention techniques in many industrial applications [3–5].

The spontaneous inclination of the materials to revert to their thermodynamically stable state or to one of their original forms first discovered is what causes corrosion, which often starts at the surface of the material. Because most metals are found naturally occurring in ores, the most stable form of low-slung energy, and because the transition from the metallic to the oxidized state results in a net drop in free energy, or G, metals are often more susceptible to corrosion [3,6,7].

About 85% of the yearly steel output globally is carbon steel, the most used engineering material. Carbon steel is utilized in significant quantities for naval uses, equipment for building, metal processing, petroleum extraction and refining, and chemical processing despite having just a modest amount of corrosion resistance [8–11].

The amount of corrosivity in water is significantly influenced by salts present in it. The primary ions in water are nitrate, sodium, calcium, magnesium, bicarbonate, chloride, and sulfate. Chlorides have maybe attracted the most interest in studies on how they impact corrosion. Similar to other ions, they increase the electrical conductivity of the water, making it simpler for corrosion currents to move. Even though nitrate is frequently present at much lower concentrations, its effects are strikingly comparable to those of chloride [12–14].

There are several ways to prevent materials from corrosion , including coating, cathodic, and anodic protection. We would exclusively focus on impressed current cathodic protection (ICCP), which is frequently utilized in protecting large structures or components, in this study. The usage of an external DC power source that is powered by common AC current is necessary for ICCP systems. Utilizing ICCP systems has a number of significant benefits, including limitless current output capacity, changeable out capacity, and a cheaper cost per ampere of cathodic protection current [12,15–17].

Anodic and cathodic protection, paint as a protective coating, choosing the right materials, including inhibitors, and good design are all important. Numerous variables, such as price, accessibility, and environmental pollution by corroding metal, among others, affect the approach choice. According to the potential difference between the structure and the anodes that has to be insulated, the cathodic protection system using sacrificed anode provide protective current. Therefore, any metal in the electromotive force series that is more active can theoretically be employed as an anode material if the structure is made of iron or steel [18– 20].

1.2 The Aim of the Thesis

The purpose of present work is to construct impressed current cathodic protection (lccp) system to prevent from corrosion. Metal pipes made of carbon steel were selected for the structure in the current work. The experimentally investigated variables are cathode length (L) distance between cathode and graphite electrode (anode) (x) and NaCl concentration (C) at variables temperature (T).

CHAPTER TWO

Theoretical and Literature Review

2.1 Overview

Corrosion is the breakdown or destruction of a substance. Corrosion causes the metal to deteriorate because of an electrochemical or chemical reaction between the metal and its environment. Corrosion, in one of the most common ways it is used, is the loss of electrons generated by metals' reactions with oxygen and water [3,5].

A current exit a structure at the anode site travels through an electrolyte and then returns to the structure at the cathode site during the electrochemical process of corrosion as illustrated in figure 2.1. For instance, a small portion of a pipeline may be anodic because the area surrounding it has lower resistivity than the remainder of the pipeline. At the anode location, current would exit the pipeline, travel through the environment, and re-enter the pipeline at the cathode site [6,8].

Anode and cathode potential differences induce current to flow. That is, the corrosion current is fueled by the fact that the anode potential is more negative than the cathode potential [6].

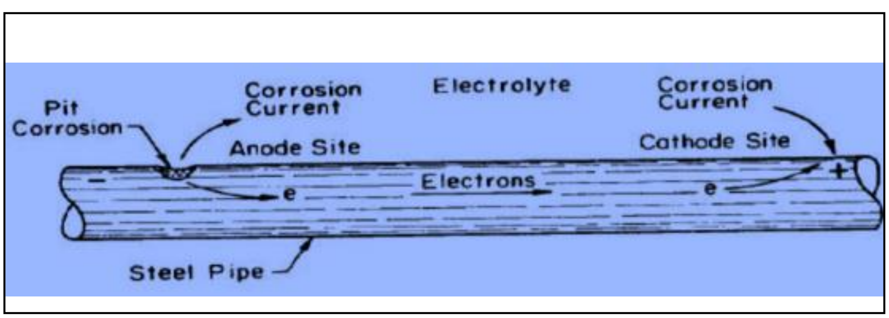

Figure 2.1 Localized Anode and Cathode Corrosion in a Pipeline.[6,8]

2.2 Corrosion Cell

A corrosion cell (also known as an the electrochemical cell or thegalvanic cell) is a circuit composed of

- Cathode
- Anode
- Electrolyte
- Metallic route (A link that allows electricity to pass between the cathodes and anodes).in figure 2-2

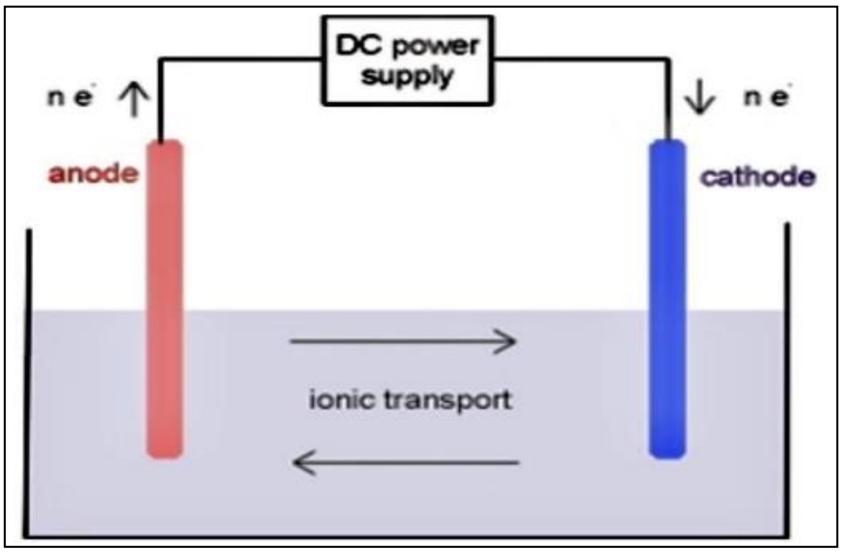

Figure 2.2 Schematic of corrosions cell [21].

The electrochemical corrosion process would stop if any of the aforementioned elements is absent or dysfunctional. Consequently, it is clear that these components are essential for preventing corrosion. The notions of corrosion cells form the basis for corrosion mitigation principles [7,22].

The corrosion reaction may be thought of as cyclic phenomena in which each electrochemical cell component must function for the corrosion reaction to continue as a whole.

In the presence of air access, iron corrodes in water as follows: $2Fe \rightarrow 2Fe^{2+} + 4e^-$ $E_o = 0.45V$ Oxidation **(2.1)**

The result, ferrous hydroxide, is often oxidized even further to produce magnetite (Fe_3O_4) or rust Fe $(OH)_2$. The nonmetal and metal processes may be handled independently in equation 1 [23].

$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$	$E_0 = 0.4\,V\ Reduction$	**(2.2)**
$2Fe + O_2 + 2H_2O \rightarrow 2Fe(OH)_2$	$E_0 = 0.85\,V\ Total$	**(2.3)**

There are three primary cell types that participate in corrosion processes [7,22]:

- Concentration Cell
- Differential Temperature Cells
- Dissimilar Electrode Cells

2.3 Corrosion Categorization

There are several ways to classify corrosion. Corrosion is sometimes separated into low temperature and high temperature categories. The other classifies corrosion as either electrochemical or direct chemical. The classification recommended here is [2]:

- Dry corrosion
- Wet corrosion

2.3.1 Dry Corrosion

Dry corrosion happens when there isn't a liquid phase present or when the environment's dew point is exceeded. Usually, the coronets are vapors and gases. High temperatures are most frequently connected with dry rusting. The attack of furnace gases on steel is one example.

Any quantity of moisture present, no matter how small, may dramatically alter the corrosion. For instance, wet chlorine, or chlorine dissolved in water, is very corrosive and affects most common metals and alloys while dry chlorine is almost non-corrosive to ordinary steel.

Oxidation, tarnishing, and scaling, are the three most significant types of these processes, which are often metal/gas or metal/vapor reactions involving non-metals including halogens, oxygen, Sulphur vapor, hydrogen sulfide, etc. The fact that the first metal oxidation, non-metal reduction, and compound reduction production must take place in the same location at the metal/non-metal contact is a hallmark of these reactions [24–26].

2.3.2 Wet corrosion

When there is a liquid present, wet corrosion happens. This is by far the major cause of corrosion and typically includes aqueous solutions or electrolytes. Corrosion of steel in water or acidic liquid is a typical example.

In wet corrosion, the metal is oxidized at different locations on its surface while a solution species that acts as an electron acceptor or an oxidizing agent is reduced. As a result, electrons are transferred. The thermodynamically stable phases that develop at the solution/metal interface may be solid complexes or hydrated ions (anion or cation), which may be removed from the contact by processes like diffusion, migration, and convection [25,26].

2.4 Corrosion Attack Types

Equipment failure can be caused by corrosion in a variety of ways and in conjunction with other types of damage (wear, erosion, fatigue, etc.) [5,27].

2.4.1 Localized Corrosion

"Heterogeneities" in the environment and metal, or overall structural geometry, certain regions of the metal surface erode at a faster pace than others. Attacks can be very localized or sweeping in nature. Examples of crevice corrosion include intergranular corrosion, weld deterioration, bimetallic corrosion, deposit attack, and filiform corrosion [28,29].

2.4.2 Pitting Corrosion

Small pits that pierce through the metal as a consequence of a highly targeted assault in particular locations may eventually cause perforation. Passive metals like as aluminum alloys and stainless steel pit when certain ions, such as chlorine ions, are present [28–31].

2.4.3 Uniform Corrosion

As the name implies, uniform corrosion happens consistently and frequently predictably throughout the majority of a metal surface. Although it is unattractive, its predictability makes it simple to regulate; the most straightforward approach is to achieve the desired material thickness to the last for the whole component lifetime. Under some circumstances, this form of broad assault occurs on all homogenous metals without potential variations between any spots on their surfaces [32,33].

2.4.4 Galvanic Corrosion

Modern engineering structures are frequently created as mixed material constructions with various couplings of materials. Couplings of two or more dissimilar metals or metals with electron conductive non-metals are highly susceptible to corrosion under the following conditions ,

(i)The materials are in electrical contact.

(ii)The materials are exposed in the same electrolyte

(iii)A potential difference (usually >50 mV).

has to exist between the different materials. When two metals or alloys that are different from one another come into touch electronically in a conducting the more anodic one corrodes in a solution. [34,35].

2.4.5 Mechanical Factor and Conjoint Action of Corrosion

When a mechanical component and corrosion work together to cause a localized attack or fracture, for instance, cavitation damage, hydrogen cracking, Fretting corrosion, corrosion fatigue, and stress corrosion cracking are all types of corrosion [4,36].

2.4.6 Selective Dissolution

Dezincification, delignification, and graphitization are examples of processes that selectively remove one component of an alloy from an alloy (often the most active) [23].

2.5 Corrosion Control

The most popular ways to avoid corrosion are:

2.5.1 Materials Selection

Materials come in a variety of forms, including metals, polymers, ceramics, natural materials, glasses, and composites. The extremely competitive materials markets, the appearance of novel materials, and new processing techniques have all led to revolutionary advancements in recent years. Corrosion issues might be solved by using an alloy that resists corrosion [2,7,22].

2.5.2 Inhibitors

A substance known as a corrosion inhibitor is used when introduced in tiny amounts to a corrosive environment, slows down the pace at which metal corrodes by acting on or near the metal surface. Both the metal's properties and the environment around it determine whether a chemical is aninhibitor or not. It is practical to divide inhibitors into those that affect anodic or cathodic electrode reactions [37,38].

2.5.3 Protective Coatings

The coating purpose is to supply a barrier between the surrounding environment and metal. Protective coatings also have the added benefit of allowing for the fusion of aesthetic appeal and protection. Coatings can be categorized as metallic and nonmetallic [39,40].

2.5.4 Design

The service life of the devices is critically dependent on design configuration. The crucial aspect is that corrosion issues must be understood and taken into consideration by the designers. However, corrosion is merely one of many factors that the designer must take into account. Unless specifically required, corrosion may not be a factor that the designer finds relevant. In many cases, rust is only taken into account the design of equipment after it has already failed. The choosing of corrosion-resistant materials for a particular climate is frequently given more thought than design, which results in equipment malfunction. Materials like 90-10 copper-nickel, which are often used for condenser tubes, might fail prematurely if the flow velocity of salt water is not adequately taken into consideration in the tube design. In desalination facilities in the Gulf area, this has been a frequent finding [41].

2.5.5 Cathodic Protection

It is an electrical way to keep buildings from rusting when they are near electrolytes like soils and fluids. Corrosion can be avoided by using cathodic protection, reducing as much as feasible the gap between the anode and the cathode When the open-circuit potentials of the cathodic sites are polarized to the open-circuit potentials of the anodic sites, corrosion of the structure is entirely prevented. The ideal surfaces for cathodic protection are those that are buried or submerged,. Cathodic protection can be used on the outside of metal structures that are buried, the inside of tanks that hold electrolytes like water, the outside of metal structures along the water like The outside of buried metal structures as well as bearing pile or sheet piling. On the inside of small-diameter pipes and other locations where cathodic protection is used, electrolyte resistance makes it hard for ions to move through the electrolyte applicability [17,42,43] Corrosion will start only when both cathodic and anodic reactions occur simultaneously. The total rate of oxidation must equal the total rate of reduction. The relationship between anodic and cathodic partial currents for the above system is presented, mixed potential theory and kinetic equations were used to explain iron corrosion. Iron interfaced with an electrolyte starts to dissolve (anodic reaction) with the redaction of oxygen to form a OH^- ion. As a result of corrosion, an equilibrium state is established. Under equilibrium conditions, the rate of the reduction reaction (cathodic)equals the rate of oxidation (anodic) reaction. where the total rates of oxidation and reduction are equal is at the intersection represented as the mixed or corrosion potential, Ecorr. The current density corresponding to corrosion potential is called the corrosion current density, Icorr. At Ecorr, the rate of iron dissolution is equal to the rate of oxygen reduction. Four electrons are provided by the anodic reaction to reduce one oxygen molecule to four hydroxide anions. The difference between the corrosion potential, Ecorr, and the reversible potential, of the corroding metal is the driving force for the corrosion processes. If the slopes of both polarization curves and the exchange current densities are known, it is possible to predict the corrosion rate of iron from electrochemical data. As illustrated in Figure (2.3)

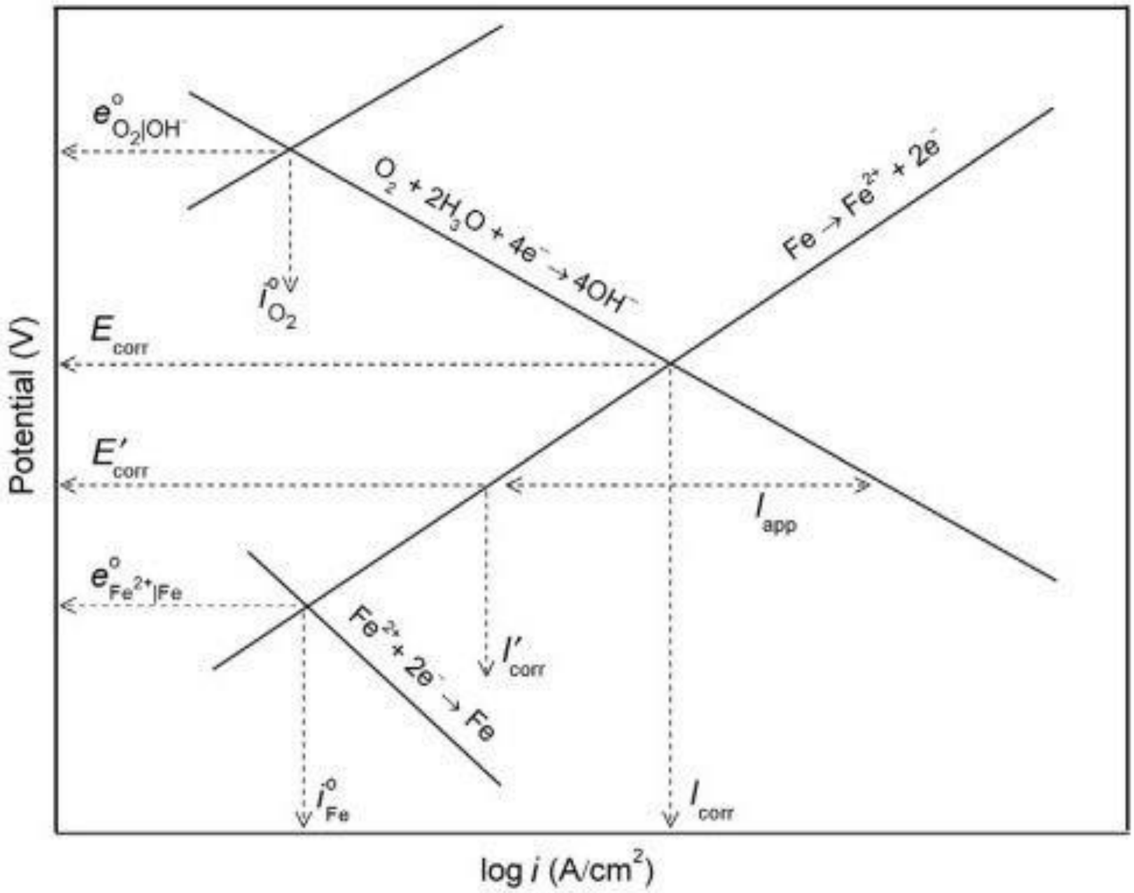

Figure 2.3 Cathode Protection Principles [18].

Impressive current and Sacrificial anodes are the two types of cathodic protections:

2.5.5.1 Impressed Current

An external power source supplies cathodic current through impressedcurrent cathodic protection devices under the influence of a DC power, the required structure, the electrolyte, and the disposable anodes safeguarded must all release current. Although the auxiliary anode's corrosion reaction generates the current, the energized materials for the auxiliary anodes are made from corrosion-resistant materials and alloys a way that either prevents corrosion or causes it to happen very slowly.

There is no difference in the materials used between impressed and galvanic current cathodic prevention techniques. However, the structure is safeguarded because of the anode's current. In a galvanic system, the anode is connected to the structure via an insulated wire, in this case. The anode acts as the source of the current, which travels through the electrolyte and then into the structure like a galvanic process.

The primary contrasts between impressed currents and galvanic systems are that the former uses an external power source to create current, often a rectifier, to convert the supply alternating current (AC) into the necessary direct current (DC). Rectifiers are able to be changed to guarantee adequate output maintenance. Over the course of the system's lifespan. Cast iron (high-silicon) or graphite anodes for impressed current cathodic protection systems are used. The main benefit of impressed current cathodic protection is that it has a significantly higher output capacity than a galvanic anode system. As a result, impressed current is frequently the solution of choice where corrosion prevention is needed for very big, inadequately covered, or naked buildings [19,20,44] in figure (2.4)

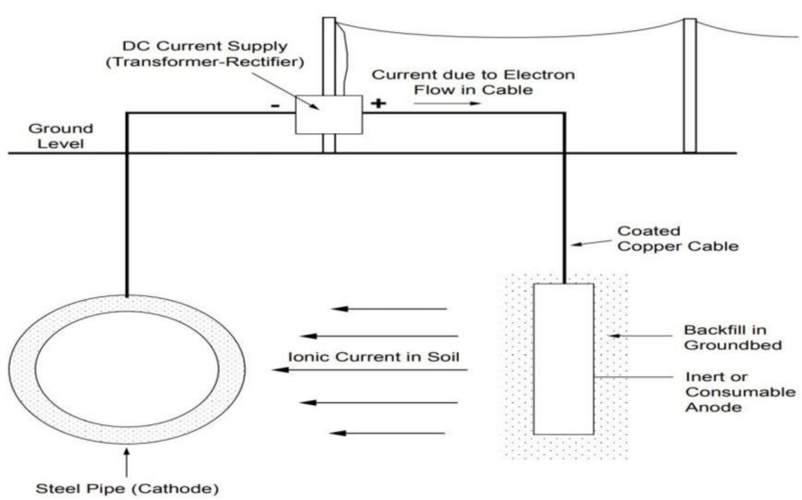

Figure 2.4 Principle of cathodic protection with impressed current [45]

The ICCP system requires the use of three main parts,
the DC power source, the auxiliary anode, and the reference electrode that is used to measure the potential of the structure.[79]

1- DC Power Source

The system ICCP requires low voltage and high current, and the source must be adjustable. Its purpose is to provide electrons to the anode regions at the surface of the structure with an equal number of electrons that are released from the anode regions to stop the corrosion

The general rectification power can be a source of cathodic protection, but the voltage changes due to changes in the external conditions, which leads to the control
capabilities leave the protection range. Therefore, a dedicated DC source has been developed that automatically adjusts the output current according to the change in the external conditions so that the capabilities of the range

2- The Auxiliary Anode

The choice of anode material for ICCP system is mainly dependent on the anode dissipation rate, the dissipation rate varies according to the environment. These anodes are made of highly corrosion resistant materials to reduce their wear rate . The anode material must meet all requirements for practical application in light of the restrictions imposed by the electrochemical dissolution rate. These conditions are:

a. Low dissipation rate.

b. High electrical conductivity and low resistance at the anode electrolyte interface.

c. High mechanical integrity to minimize mechanical damage during installation, maintenance and erosion.

d. Ease of fabrication into different forms.

e. Low cost.

Currently, the commonly used materials in this system are graphite, high silicon solid iron, mixed metal oxide (MMO), scrap steel and platinum

Graphite: It has been used as an anode material for the ICCP system for several years. It has a low consumption rate, high efficiency, low maintenance costs as well as long-life corrosion protection advantages, but it is a fragile material and can be damaged easily and difficult to transport Graphite operates at a current density of less than 10.75A/cm^2in soil and 0.23A/cm^2in water. The graphite is designed in the soil with a maximum density of 930 cm^2ampere, so if the current density is within the range, its consumption rate is 0.9 kg per year ampere. If it goes beyond the band, the graphite becomes a soft, non-conductive substance.

Iron-Silicon Anodes: An alloy commonly used in the impressed current method, which has the advantage of losing materials at a much lower rate than ordinary cast iron annually. Iron anodes include 14.35% pure silicon, and 4.5% chromium is added.to it, making it an alloy of high silicon cast iron (HSCI) to prevent pitting corrosion of pitting in seawater due to the presence of chlorine gas. At high temperatures above 100°C, applications chromium can be replaced by adding 3% of molybdenum. The disadvantages of this alloy are heavy and brittle.

MMO-coated electrode has a very low dissolution rate that may reach (5 mg / A) The service life of these anodes is up to 20 years in sea water, fresh water, soil and concrete components. The electrode coated with MMO is greened by thermal decomposition on Substrate titanium.

Platinum and Platinum-coated electrode: It is an ideal anode material. A noble mineral with high chemical stability, used in a wide range of environments such as underground, marine, concrete, and cathodic protection systems due to the very low.

3- The Reference Electrode

The reference electrode is a major and important part of the design of the ICCP system, a polarized electrode by which it determines the potential of the structure to be optimally catholically protected by placing it as close as possible to the protected structure to avoid the error caused by the IR drop in the electrolyte. The reference electrodes, which are a permanent part of the impressed current cathodic protection system, provide important feedback on how well the system performs. These electrodes are used to tune the power settings on the rectifier, periodically monitoring the life of the structure and determining whether the system is operating properly[79]

4-Effect of Backfill: uniform resistivity ,prevent anode of deterioration ,reduce anode -electro resistance ,increase porosity around the anodes (vent gas), reduce polarization effect.[45]

2.5.5.2 **Sacrif**icial anode

By using galvanic corrosion, sacrificial anode methods produce cathodic current. The structure to be guarded is metallically connected a metal or alloy that has a higher electrochemical activity than the material that needs to be shielded in order to supply the current. The anode and the structure must be near to each other. the electrolyte. Expendable anode, electrolyte, and shielded structure all experience current discharges [46].

At regular intervals throughout the pipe, zinc or magnesium anodes are connected to it. Regular lifting for examination and replacement of the anodes takes place. The piping is given primary protection by a covering such a tarred wrap in order to reduce anode usage. Coating steel sheet with a thin coating of zinc, either by electrode location or by hot-dipping (galvanizing), is one of the most efficient and affordable ways to protect it in nearly neutral aquatic conditions The zinc coating prevents corrosion in nearly neutral aqueous conditions by generating a The exposed zinc is catholically protected by corrosion, which results in the creation of Zn $(OH)_2$, which covers the exposed iron and deters further attack at coating imperfections caused by abrasion and at cut edges. [47]

Tin coatings' ability to galvanically shield steel food cans may appear unexpected. In the sacrificial anode system, cathodic protection is essentially a managed electrochemical cell. The size and quantity of current that anodes emit determine how long the anode will life.

The corrosive potentials of various metals are utilized by a galvanic cathodic protection system. If a structure doesn't have cathodic protection, corrosion will occur because one location is more negatively charged than another. However, if an object that needs to be protected, like a pipeline, is placed adjacent to one that is considerably less inert and has a much larger negative potential, like a magnesium anode, and a metallic connection is constructed between the two (such as an insulated wire), the object will act as the anode and the entire structure will act as the cathode. That is, as indicated in Fig. 2.5, the new item sacrifices itself to corrosion in order to defend the structure. The anode corrodes in a sacrificial manner to safeguard the structure, hence the name "sacrificial anode cathodic protection system" for the galvanic cathodic protection system. Due to these metals' higher negative potentials compared to steel, galvanic anodes are often built of magnesium or zinc [18,48].

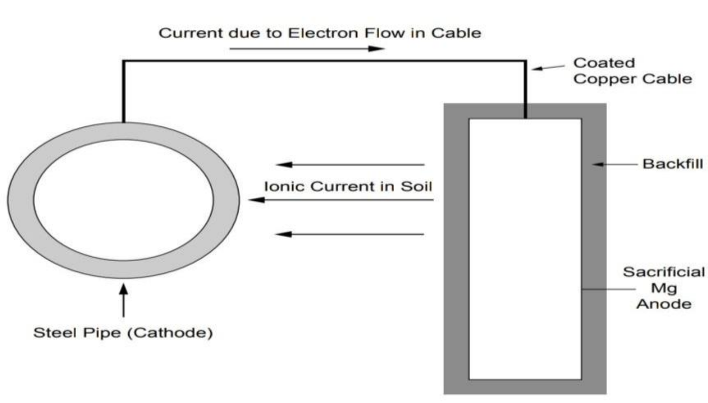

Figure 2.5 Principle of cathodic protection with sacrificial anodes [45].

Pure metals are never employed as sacrificial anodes in reality. This is due to a number of factors, including the necessity to [47,49]:

- Uniform anode dissolution ensures that all metal is utilized in a productive way for cathodic protection rather than being wasted through mechanical loss.
- a consistent, repeatable, for the anode, a negative operating potential
- A significant and repeatable anode capacity (A h^{-1} kg^{-1})
- Absence of any passivation-related anode activity loss

Table 2.1 Comparing the Impressed Current with the Sacrificial Anode System

Sacrificial Anode	**Impressed Current**
External power supply is not required	External power supply is required
The cost of investment is low	The cost of investment is high
This requires periodic replacement of sacrificial anode .	Replacement is not requires as anode are stable
Soil and microbiological corrosion effects are note considered	Soil and microbiological corrosion effects are taken into account
This is a suitable method when the current requirement and the resistivity of the electrolytes are relatively low	This is a suitable method when the current requirement and the resistivity of the electrolytes are high

2.6 Factors Affecting the Cathodic Protection

2.6.1 The pH of the Solution

A solution acidity is indicated by the pH value where the interaction between iron and aerated water at ambient temperature is firstly considered (aerated water hold dissolved oxygen). Corrosion rates are strongly affected by the pH range (between 4 and 10), which determines how quickly oxygen reacts with absorbed hydrogen. The surface is depolarized and the reduction process may continue as a result. Below a pH of 4, ferrous oxide becomes a soluble solid. The oxide is not deposited as the metal surface coating but rather dissolve as it is produced. Metal surfaces directly interacts with the acidsolution when the protective oxide coating is absent, which speeds up the corrosion reaction compared to higher pH levels. Furthermore, it is noted variables [O_2 reduction reaction (depolarization) and H_2 evolution], revealing that the rate of corrosion, with a pH below 4, oxygen depolarization is no longer necessary for hydrogen synthesis. A synergistic effect between hydrogen ion reduction and proton reduction is responsible.

When the pH is increased above around 10, the corrosion rate begins to decrease. This is believed to be brought on by a faster reaction between oxygen and Hydrated FeO in the oxide layer, which produces the more defensive Fe_2O_3 [50,51].

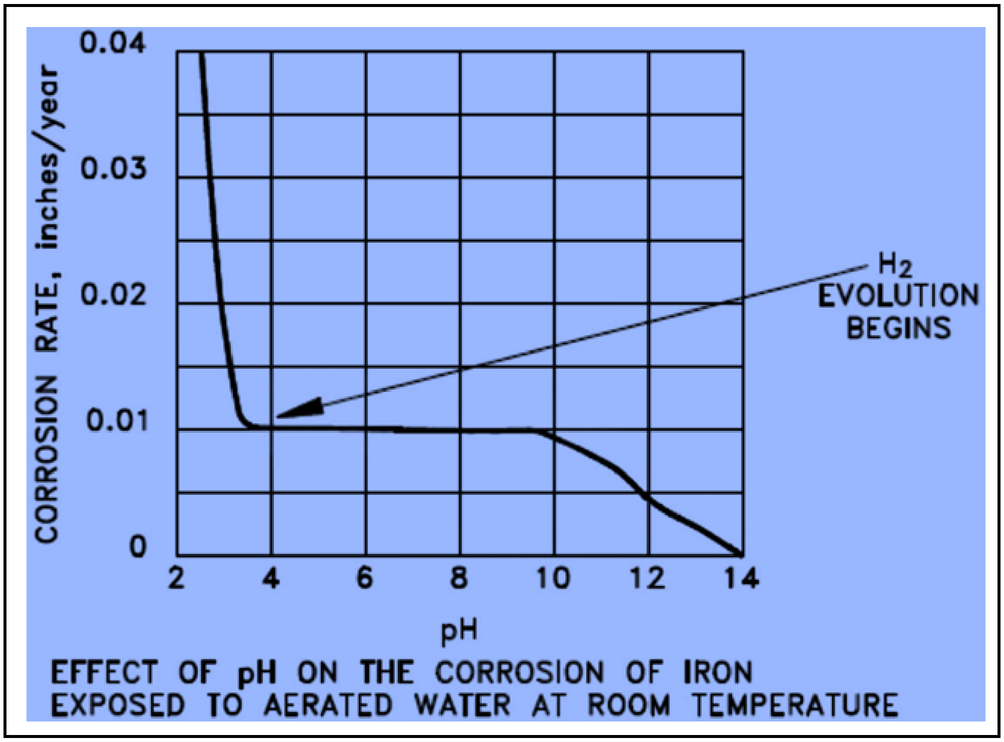

Figure 2.6 Effect of pH on corrosion rate of iron [52]

2.6.2 Influence of Velocity

Given the impact of flow on both anodic and cathodic processes, fluid velocity is one of the greatest crucial factors to be taken into account during metal corrosion. The relative mobility of the metal and the corroding environment might have distinct effects on the corrosion process. By increasing the heat and mass transport of reactants to and from the surface of the corroding metal, this relative movement can speed up the corrosion process. The loss of protective coatings, wear, and erosion, on the metallic surface may also happen when solid particles are present.

The system's physical shape clearly influences how velocity impacts the limiting diffusion current. Furthermore, when the flow state are laminar as opposed to when turbulence is present, the velocity has a distinct impact on the diffusion process. The following equation may be used to describe the limiting diffusion current under most circumstances [55,56].

$i_L = K \times u^n$ **…… (2.4),**

Where(i_L)is limiting current density

(K) is a constant, (u) denotes the environment velocity in relation to the surface, and (n) is a constant for a specific system. The range of n values 0.2 to 1.

Until the junction of the cathodic and anodic polarization curves occurs at a current smaller than the limiting diffusion current, the corrosion rate would be directly relative to the limiting diffusion current. Prior to cavitation’s or erosion changing the system physical makeup at higher velocities, the corrosion rate will be mostly independent of velocity [55,56] .

The common increasing agitation or solution velocity observations are shown in Figure 2.7. According to curve B, the velocity or agitation have little impact on the corrosion rate for processes controlled by activation polarization. The corrosion rate rises with agitation or velocity if the corrosion process is catholically controlled, as illustrated in curve A, section 1., this effect happens when an oxidizer, such dissolved oxygen in acids or water, is present in extremely minute concentrations. When the metal is easily passivated and the process is regulated by diffusion, as evidenced by the behavior in sections 1 and 2 of curve A. [57]

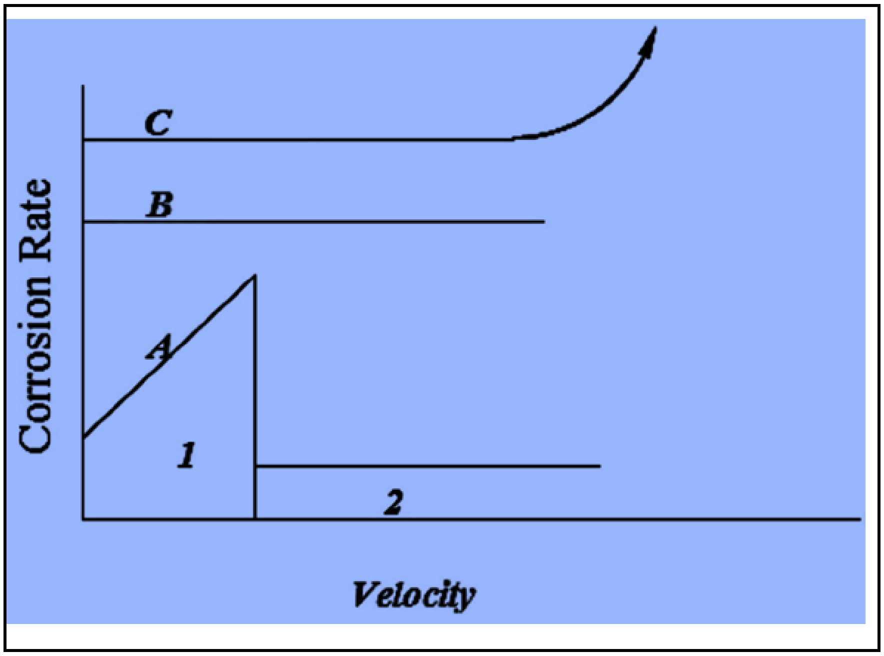

Figure 2.7 Effect of Velocity on the CR [57]

2.6.3 Influence of Temperature

Nearly all chemical processes speed up as the temperature rises. The temperature variation has the biggest impact when the activation process determines rate. According to the size of the activation energy, the activation mechanism may be boosted by 10-100 times if diffusion rates double for a certain temperature rise. The rate of corrosion on metal is significantly influenced by temperature. When corrosion occurs in a neutral solution, a change in temperature affects the rate of oxygen diffusion and theoxygen depolarization overpotential favorably, but it reduces the solubility ofoxygen. Due to a reduction in the hydrogen evolution overpotential, corrosion in an acid media occurs more quickly as the temperature rises [38,58].

When oxygen diffusion controls corrosion, the rate of corrosion Every 30°C increase in temperature causes the oxygen concentration at a given temperature to about double. The corrosion rate increases with temperature because oxygen cannot leave a closed system, till all of the oxygen is used up. According to Figure 2.8, the rate of growth when corrosion is accompanied by hydrogen evolution will for every 30°C increase in temperature, more than double [59,60].

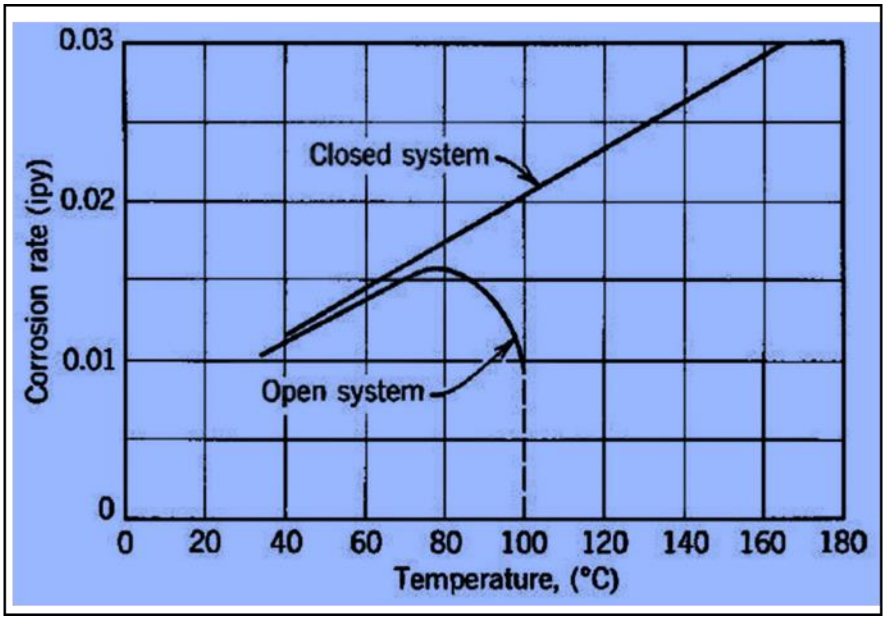

Figure 2.8 Effect of temperature on corrosion of iron in water [59].

2.6.4 Influence of Dissolved Salts

Chloride, sodium, bicarbonate, sulfate, calcium, magnesium, and nitrate are the major ions in water. There could occasionally be potassium salt residues, which behave very similarly to sodium salts.as well as a few PPM of iron or manganese. The modest amounts of other acid radicals present, such as phosphate, nitrite, iodide, fluoride, and bromide normally have minimal relevance from the perspective of corrosion.

Some of these ions, particularly nitrite and phosphate, may inhibit corrosion at higher concentrations, although their tiny amounts in natural waters normally have minimal impact. In terms of research on how chlorides affect corrosion, chlorides have perhaps garnered the most attention. They improve the water electrical conductivity, much like other ions, making it easier for corrosion currents to flow [3,10,22]. Although nitrate is often present at considerably lesser amounts, its effects are remarkably similar to those of chloride. Concrete can really be harmed by high-sulfate fluids, and sulfate seems to have a negative effect on how well particular inhibitors work. Additionally, sulphates have a unique function in bacterial corrosionin anaerobic environments. Iron and steel corrosion rates are influenced by alkali-metal salts such as NaBr, **,** KI, LiCl,KCl etc. in a similarway as sodium chloride. In the sequence Li, Na, and K, chlorides seem to be a little more corrosive. At low concentrations (0.2 to 0.25 N), nitrates could be a little less corrosive than chlorides or sulfates, although greater quantities aren't always better. The slight variations between all of these solutions may result from, for instance, their unique impact on the Fe $(OH)_2$ diffusion-barrier layer, or they could be caused by the ions various adsorptive properties at a metal surface, which could lead to different anode-to different over voltage characteristics or cathode area ratios for oxygen reduction [14,61,62].

2.7 Kinetics of Corrosion

The process of creating and consuming electrons is called corrosion. Electron flow may be measured as current, and Faraday was the first to discover a connection between the exchange of electrons and mass reactions [63].

m = (I t a) / n F..**(2.5)**

I = current (m A/cm^2)

m = mass reactedt

t= time (minutes)

a = atomic weight (g)

n = number of equivalents

F = Faraday constant (96.500 coulombs / equivalent)

To evaluate the corrosion rate, the following equation is appliedr

cr= (i a) / n F **………(2.6)**

cr = corrosion rate

i= current density

Every reaction has a distinctive equilibrium current density, known as io.

2.8 Cathodic Reaction in Corrosion

In the process of metallic corrosion, a number of various cathodicreactions are typically observed.

The essential two cathodic reactions in corrosion metals are the oxygen reduction reaction (ORR) and hydrogen evolution reaction (HER). This is because Water molecules and hydrogen ions are always dissolved oxygen molecules are typically present in aqueous solutions (solutions with water as the solvent). Also, because most aqueous solutions come into touch with the environment, they are also commonly present [3].

Because no other cathodic process is HER, it governs the pace of the anodic reaction in the absence of oxygen or any other oxidizing species-specific metal if the polarization is small (cathodic control). However, in the presence of dissolved oxygen, both cathodic reactions will be possible. The pace at which corrosion occurs depends on factors such as the solution pH, the metal or ion reversible potential system, and the surrounding temperature.

It should be noted that the activity of H_3O^+ is too low in neutral or alkaline solutions for it to participate in the reaction, pH, but the type of metal and metal oxide will also have an impact. In these cases, the water molecules will serve as electron acceptors [64].

(alkaline solution)

$H_2O + e^- \longrightarrow \frac{1}{2} H_2 + OH^-$ … (2.6)

(Acid solution)

$H_3O^+ + e^- \longrightarrow \frac{1}{2} H_2 + H_2O$ … (2.7)

For oxygen reduction reaction

(Alkaline solution)

$\frac{1}{2} O_2 + H_2O + 2e^- \longrightarrow 2OH^-$ … (2.8)

(Acid solution)

$\frac{1}{2} O_2 + 2 H_3O^+ + 2e^- \longrightarrow 3H_2O$ … (2.9)

It should be noted that the pH of the diffusion layer will rise as a result of both reactions (2.6) and (2.8).

The hydrogen evolution reaction happens when the hydrogen iondistribution in the solution next to the electrode surface is quite uniform. The area close to the electrode surface will lose hydrogen ions at greater reduction rates.

A limiting rate will be achieved if the reduction rate is raised further, and it defined by the diffusion rates of hydrogen ions to the electrode surface [65].

2.9 Previous works

Authors	Years	Important results
Shaker S. Al_Kelaby	2002	Designed an impressed current cathodic protection system to prevent corrosion on metal specimen (cathode) using graphite electrode as anode. The performance of the CP process has been tested for four major factors that affect the process, these are: the specimen length, the distance. The impressed current and concentration. His results show that the cathode length does not affect limiting current density, cathodic protection current density and free corrosion rate [42].
S. M. Saleh	2005	Studied the effect of different three variables such as NaCl concentration distance between cathode and anode and the temperature on the cathodic protection current density in order to protect submerged pipelines from corrosion. The structure used is carbon steel metal pipe. The carbon steel results showed that the cathodic protection current density increases with increasing the above studied variables. Also (ICP) showed sharp increasing when the fluid was stirred. The corrosion potential becomes more negative as temperature increases so that cathodic protection criterion is investigated to be more

		negative to some extent in order to make adequate protection [66].
AL-Jawary	2005	Investigated the impact of cathodic protection current density of buried pipes in soil on the distance between cathodes and anodes. He came to the conclusion that as that distance increases, so does the density of the protective current [67].
S.A. Ajeel,and G.A. Ali	2008	The effect of several factors on cathodic protection for steel tubes immersed in sea water was explored. The variables under study include pH solution of (5.0 - 9.0), distance between pipe (cathode) and graphite electrode (anode) of (10 - 20 cm), concentration of (0.01- 3.5) % NaCl, temperature of (30 - 50°C), and a specified range of these variables. The electrochemical results reveal that as temperature and concentration increase, so does the density of cathodic protection current. The current density increases slightly as the distance between the cathode and anode increases. These parameters' effective sequence on cathodic current density is as follows: Temperature > concentration > pH solution distance cathode – anode [68].
Basim O. Hasan	2010	Investigates the effects of salt concentration on the corrosion rate of carbon steel in aerated

		solutions under turbulent flow conditions (Reynolds number= 15000- 110000 and temperature of 30-60C˚). The findings showed that, across the whole range of Re and temperature under investigation, the salt content had a significant impact on the corrosion rate. The seawater environment showed the highest rate of corrosion (3.5 % NaCl). Although it is less than throughout the entire range of Re and temperature, distilled water also exhibits a considerable rate of corrosion. The two key variables, oxygen solubility and diffusivity, are changed by temperature, which has an impact on the rate of corrosion [69].
Lotto et al.	2011	Noted that in a seawater environment, aluminum anodes performed better as sacrificial anodes for mild steel. The zinc anode performed better as a protector in a sulfuric acid environment than the aluminum anode. The zinc anode wasemployed in different sizes, which proved that the anode's size affects how well it performs cathodic protection. Larger anodes provide more electrons to protect thecathode and take longer to repair [70].

B.O. Hasan,and M.F. Abdul-Jabbar,	2012	studied ICCP system for low carbon steel pipe. They investigated the influence of temperature under stationery and flow conditions on the minimum cathodicprotection current that would provide a full cathodic protection for steel tube (cathode) in 0.1N NaCl solution (pH=7) and graphite electrode (anode). For temperature range of 35-55°C, the impressed current required for cathodic protection depends on temperature and rotational velocity. Applying I=2Icorrr. gives protection percent between 90 to 99%The protection percent increased with increasing impressed current (Iccp) due to the increased reduction of O2 at the metal surface leading to decrease the corrosion of metal [71].
A.A. Atshan, B.O. Hasan, M.H. Ali,	2013	Investigated the effects of anode type, solution temperature, anode to cathode length (or area), and anode to cathode ratio on the ICCP of carbon steel pipe in NaCl solution. The results for both graphite and scrap iron electrodes demonstrate that a decrease in protection efficiency is caused by a greater distance between the anode and cathode.

		The efficiency of the corrosion protection increases with the area ratio of cathode to anode. Following the applicationof the protection, the protection potentialtypically changes to a more positive state. Protection potential and protection current are both affected by anode type and solutiontemperature, which causes the protection current to significantly drop with time [72].

M. S. Hashim et al.	2014	Employed carbon steel pipe (ASTM API-5L) type as X60 steel and graphite as anode in Impressed Current Cathodic Protection (ICCP) System. In order to examine the effect of the conductivity different weights of NaCl were dissolved in distilled water. The results show that, the impressed current needed forprotection increased whenever the electrical conductivity of a solution increased with an increase in salt concentration [73].
B.N.A. Sada, R.S. Ali, K.A.M. Ali,	2016	Studied the effect of several variables insaltwater such as conductivity, temperature, and aeration flow rate on the ICCP system. The experimental results showed that the current is raised for increasing any variable [74].
H. Elfergani, A. Abdalla,	2017	Investigated the effect of sodium chloride concentration (NaCl wt%) on the corrosion rate of carbon steel. There were two cases considered: aerated solutions and non- aerated solutions. The results showed that increasing the NaCl concentration increases the corrosion rate to a maximum of 3 % wt NaCl and then gradually decreases due to the creation of a passive iron oxide layer. The presence of dissolved oxygen in the water

		or salt solution has been observed to increase the corrosion rate several times. In the worst-case scenario, zinc electrode proved effective in preventing steel corrosion in SACP [75].
F.K. Matloub et al	2018	Studied ICCP system for low carbon steel pipe. They investigated the influence of pH, sodium chloride concentration, and applied cathodic current. The results showed that, the corrosion rate decrease with increasing pH and ICCP and increases linearly with increasing salt concentration [13].
K.A.M.A, Hassan F. Faisal,	2018	Discussed how four significant parameters affected the ICCP system and corrosion of carbon steel. The anode-cathode distance, pH value, dissolved oxygen ratio, and solution temperature are these parameters. The findings of the experiment demonstrated that the impressed current increases with increasing solution temperature, oxygen concentration, and distance. However, it decreases when pH increases [76].
Hanif et al.	2019	Compared the ICCP and SACP (Zn anode) systems using a steel sample exposed to different ionic liquid concentrations. To supply

		impressed current for ICCP, three different voltage sources of 6v, 9v, and 12v are connected to the specimen of mild steel.The ICCP system was found to be better compared to the sacrificial system in highly corrosive environments. At 6 volts, both systems are equally effective. The corrosionrates of 9v and 12v, on the other hand, werelower than those of SACP. Furthermore, the corrosion rate decreases with time as a result of the formation of a layer of rust on the surface [49].
N. Ali et al.	2019	Investigated the corrosion rate of carbon steel in aerated solutions in different corrosive environments. Samples have been exposed to NaCl solutions of 2%, 3%, 4% and 5% concentrations. The findings showed that, the initial corrosion rates were higher for all NaCl concentrations and the gradually decreased due to increased exposure time. The average value of corrosion rate was in the range 0.247 μm/year [77].

Bawa et al.	2020	Investigated the influence of anode materialon an impressed current cathodic protection system. Four different anodes were utilized to evaluate their performance (Aluminum 90.6 % / Copper 9.4 %, Copper 90 %, Aluminum 10%, Copper 95 %, Aluminum 5%, Lead 100%). It was determined that the lead anode has a low dissolution rate and is the optimal material for an ICCP system, as it is inexpensive and readily available for buried and submerged buildings in harsh settings [78].
F. S. Al Masoodiet al	2021	Studied how various parameters for boththe SACP and ICCP systems affected the rate of corrosion of carbon steel. Temperature, salt concentration (conductivity), open circuit voltage, and pH were among the variables observed. The results indicated that the protective current density increases with temperature andconcentration due to an increase in ion mobility, as the solution conductivity increases, and with a decrease in pH. The experimental findings demonstrated thatraising the DC current causes the cathodic protection current to increase. The higher the DC power supply, the more effective the ICCP method is in comparison to the SACP method [79].

CHAPTER THREE

Experimental Work

3.1 Introduction

The purpose of this chapter is into the cathodic protection system for carbon steel pipe in 5g/L,10g/L, 20g/Land 35g/LNaCl solution. In this study, a cathodic protection system with impressed current is used. The experiments were carried out at different temperature and different concertation and different distance between cathode and anode.

3.2 System Information

The following is a list of the equipment and supplies used in the tests and their Information:

a. Working Electrode (Cathode)

A low carbon steel pipe with dimensions of 5 cm in length and 2.58 cm outer diameter was used as the working electrode. Table (3-1) displays the analytical chemical composition of carbon steel, pipe in Ministry of Industry and Minerals State Company for and Engineering Rehabilitation (slER) Engineering ins and lab Department, Baghdad, Iraq.

Table (3-1): Carbon Steel pipe composition under consideration

Element	C%	Mn%	Si%	S%	P%	Mo%	Ni%	Al%	Cr%	Fe%	Cu%
Volume	0.202	0.496	0.241	0.0078	0.0217	0.0032	0.0063	0.0169	0.0124	Bal.	0.0041

b. An Extra Electrode (Anode)

The anode electrode was a graphite rod with a high conductivity . with 1.5 outside diameter, and a length of 3.5 cm, located horizontally opposite the working electrode at the same level (cathode).

c. Reference Electrode

A saturated calomel electrode was used to determine the cathodic potential (SCE). At the starting edge of the cathode length, a short the reference electrode's capillary bridge was positioned within 1-2 mm of the cathode's side.

d. Glass Bath and beaker

A glass basin of (600 x 300 x 200) mm dimensions is used in the experimental work, which includes all components of the experiment such as the anode, cathode, reference electrode and beaker (3L).

e. Thermometer

A Glass thermometer used to measure the temperature of the solution up to 100 thermostat water bath type (ds) kw-1000dc.Thermo stirrer heater type (Gallen hemp).

f. Digital balance

A digital balance with four decimal points (Sartorius BP3015).

g. Power supply

DC power supply is used to apply voltage type rang manufacture p.35, pE 1510, 0-35v

h. Voltmeter and Ammeter

They are the measuring devices of UNI – T type UT33B + which are used to Measure the current between the cathode and the anode and the voltage of the Structure with respect to the reference electrode.

i. Sodium chloride

Sodium chloride: NaCl, 99.55% supplied by Thomas Baker (Chemicals) pct. LTD.

v. Distilled water

Supplied by research lab Chester in Eng. Chemical Departments, And demineralized water\dm water.

k. Solvent used

There is one type of solvent used to clean the metal specimens

L. Ethanol

C_2H_5OH of concentration ≈ 70 % supplied and 30% distilled water Khari Al-judo Co for manufacture of Detergents. Disinfectant and Antiseptics.

3.3 preparing the cleaning solution

A 1% solution of HCI is needed to clean the metal sample before and after each test. This solution was made according to the dilution law:

$C1V1= C2V2$

C1: the concentration, first

C2: the concentration second,

V1: the volume first,

V2: the volume second.

3.4 Electrical Circuit Connection

The electrical circuit included the following components:

A. D.C power supply (type: PE 1510 and range 0 – 35 V) It provides improved stability and control and can be utilized for potential static and is commonly equipped with current and voltage limiters.

B. Multi-range Ammeter

A digital Multi-range Ammeter (type: Total. Tat 47503).

C. Multi-range Voltmeter

Range of (0.1 – 1000) mA A digital Multi-range Voltmeter (type: unlit Ut803) with a range of (0 – 2500) mV.

A- Multi-range Resistor (Resistance Box)

A variable resistance (Type: DR4/ABCD) with a range of (0-10) MΩ.

3.5 The Specimen Preparing

The carbon steel pipe is prepared for each experiment (working electrode) cutting a length of 5 cm and an outside diameter of 2.58 cm .All specimens were grind after that it polished by using polish cloth , washed with distilled water. The specimens immersed in 1% HCl solution with 60g inhibitors (hexamine) per liter of HCl solution for 30 minutes prior to each experimental running shed with distilled water, dried with a paper tissue, then immersed for 2 minutes in annular Ethanol and dried again. A four-digital balance is used to weigh the sample (ASTM)

3.5.1 Weight Loss Experiments

After supplying the cell with solution and electrodes, the electrical circuit is opened and the equilibrium potential assumed by the metal in the absence of current is measured. The Open Circuit Potential (OCP) refers to the connections to the metal. The measurement of Eco is usually the first step in electrochemical corrosion investigations. Within 45 minutes, the cell's system often attained its steady state value after 2h. And also measured weight loss.

The corrosion rate was also measured at different temperatures (20, 30and40)˚C, and at different Nacl concentrations.(5,10,20and 35)g/land different distance anodic and cathodic (2,25and 50) cm.

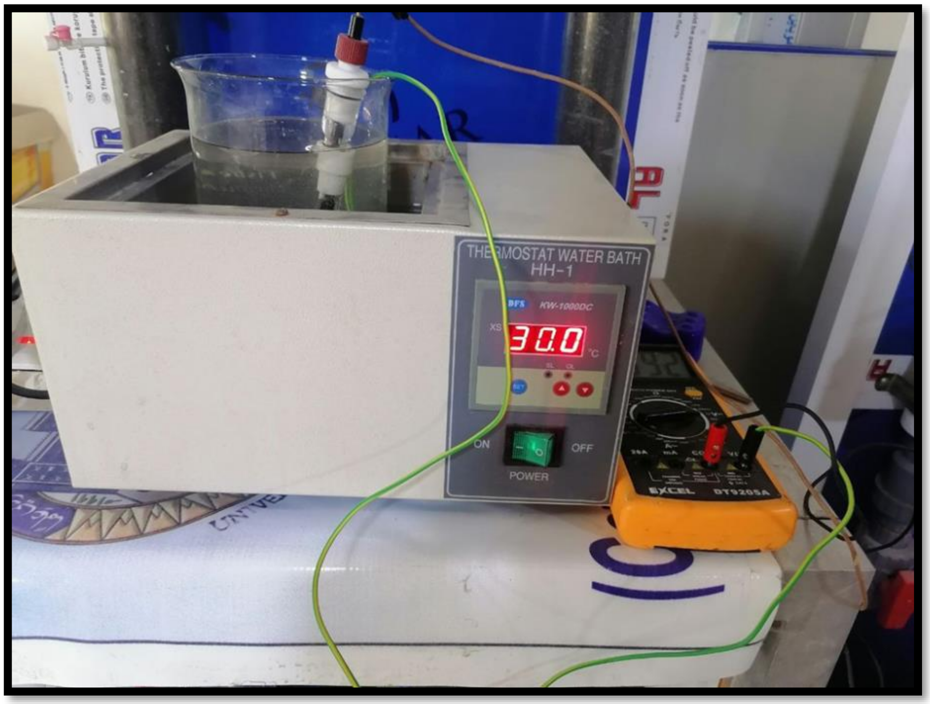

Fig. (3-1): The Test Apparatus Weight Loss

3.5.2 Impressed Current Cathodic Protection procedure (ICCP)

The specimen (cathode) was cut from a carbon steel pipe at a length of 5 cm and an outside diameter of 2.58 cm. after the specimen Preparing in section (3-4) and the salt solution of Nacl and distilled water added to the glass bath the Nacl concertation are (0.5,0.1,0.2 and 3.5)% NaCl (5, 10, 20 and 35g NaCl per liter distilled water)

The lugging capillary tube the salt bridge was shown very near to the steel specimen, around one millimeter apart, to prevent the IR drop.. Before beginning the experimental run, The bath's heater controller was then set to the required temperature. (between 20, 30 and 40)°C to achieve thermal equilibrium and the distance between cathodic and anodic are (2, 25 and 50) cm To prevent water from entering the surface of the inner tube, the cross-sectional area of the specimen was sealed at both ends with rubber before being covered in thermal silicon. After the working and auxiliary electrodes had been inserted into the electrolyte at equal levels from the top and bottom, as well as a distance of 4cm, the other end was connected to the electrical connection (connection point) and secured into a plastic stand. A multi-range voltmeter was used to measure the electrode potential in relation to a saturated calomel electrode. The galvanostatic method kept the D.C. power supply voltage constant at 10 V. while the circuit resistance was changed until a potential value of change of resistance of -0.65v and -0.85V vs SCE was achieved. The experiments were stopped when the impressed current (lcp) reached steady state, providing the best impressed current cathodic protection. This value was measured using a digital ammeter at intervals of recorded each 15 minutes over the space of four hours, and when silica gel was used, it was left in the dictator for 24 hours.

Each run was repeated in order to assess how the researched parameter such as temperature, NaCl concentration, and cathode to anode distance(2,25and 50) cm affected the (ICCP). A digital four-point balance used to weigh the final result.

Fig. (3-2): The Test Apparatus

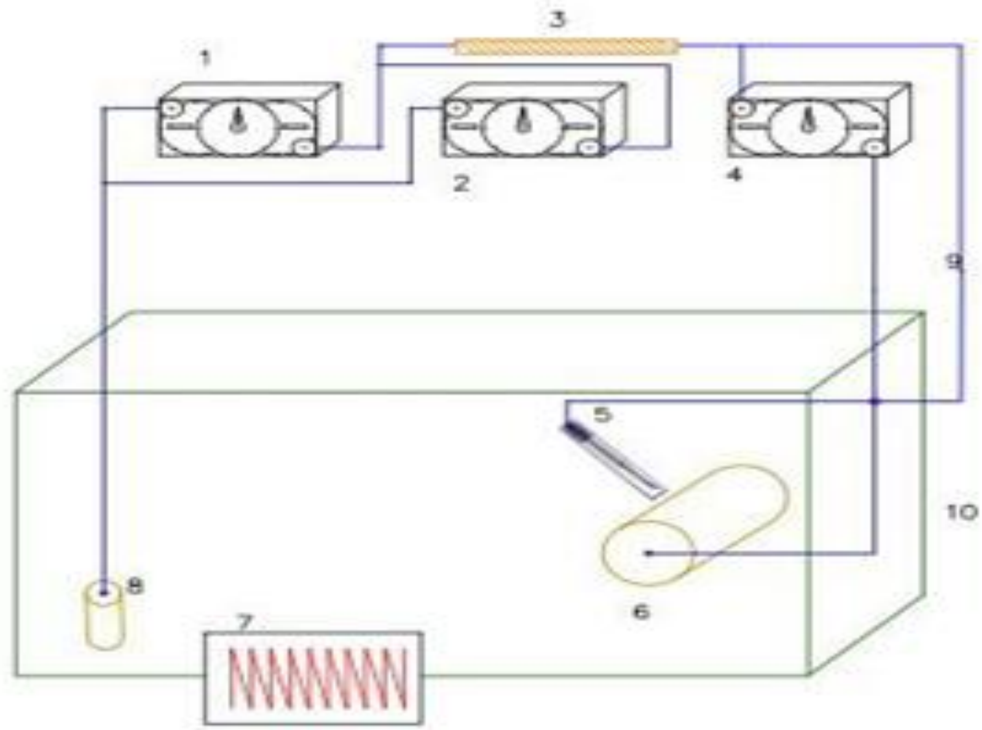

Figure (3.3) Schematic Diagram of the Installed ICCP system,(1) D.C power supply(2) Multi-range Ammeter,(3) Resistance Box,(4) Multi-range Voltmeter,(5) Saturated calomel Electrode(SCE),(6) Cathode,(7) Heater,(8) Anode,(9) Connecting wires,(10) glass water.

CHAPTER FOUR

Result and Discussion

4-1 Introduction

The section main objective is to determine the cathodic protection current density (impressed current density) that can be used to protect carbonsteel pipes by reducing the corrosion current to zero. The behavior of carbon steel in solutions of 5 g/L, 10 g/L, 20 g/L, and 35 g/LNaCl was studied using the open potential circuit (opc) method employing the potentiation approach. All experiments, the cathode (the electrode working) and the anode (the electrode auxiliary) distances of 2, 25, and 50 cm. In order to show how these factors determine impressed current, three different solution temperatures (20, 30, and 40) °C and a length of carbon steel 5cm were used. The potentials of the electrodes are shown in reference to a saturated calomel electrode (SCE). Values are provided per unit area, or current density, in the tables. The conclusions that have been presented are the average values from numerous successful and consistent experimental runs.

4.2 Open Circuit Experiments

The corrosion potentials (open circuit) at different concentration at constant temperature were plotted in figures. (4.1 to 4.4) and are shown in Table (4-1)

Table 4-1: Corrosion Potentials at Different concentration

Concretion (g/L)	5	10	20	35
Ecorr (V)	-0.730	-0.749	-0.758	-0.776

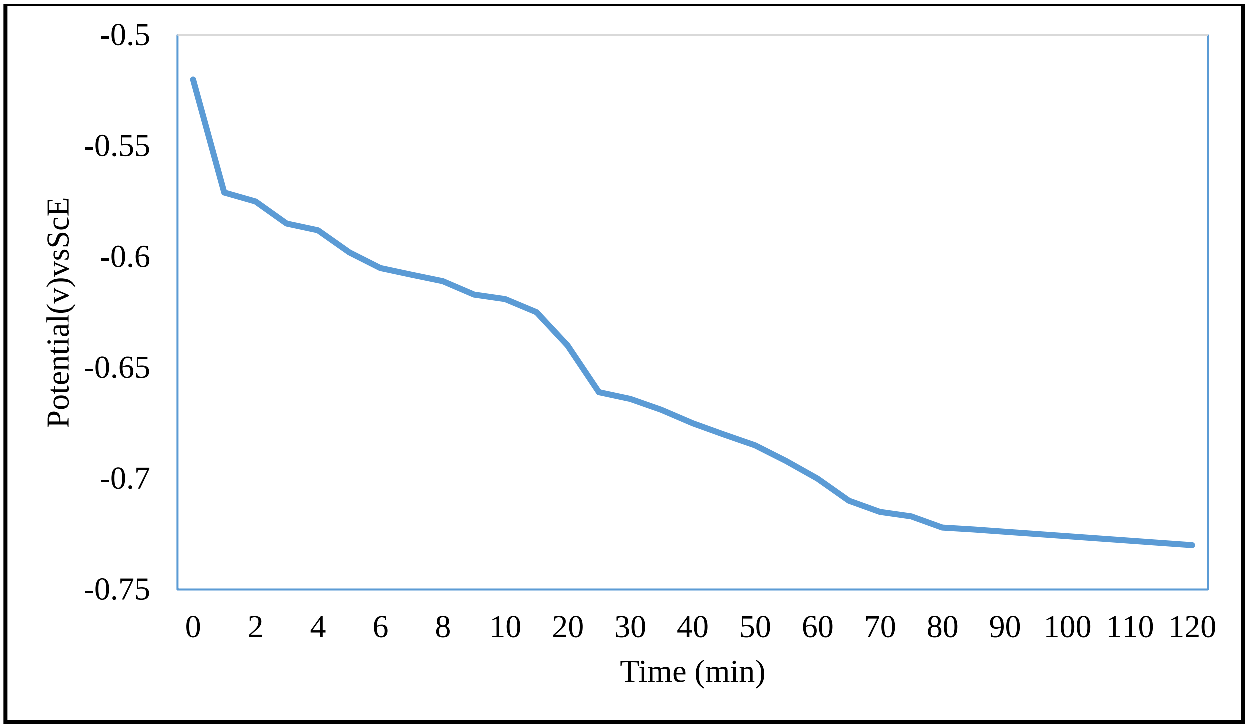

Figure (4-1) Potential vs time for carbon steel in 5 g/L NaCl solution at T=20˚C

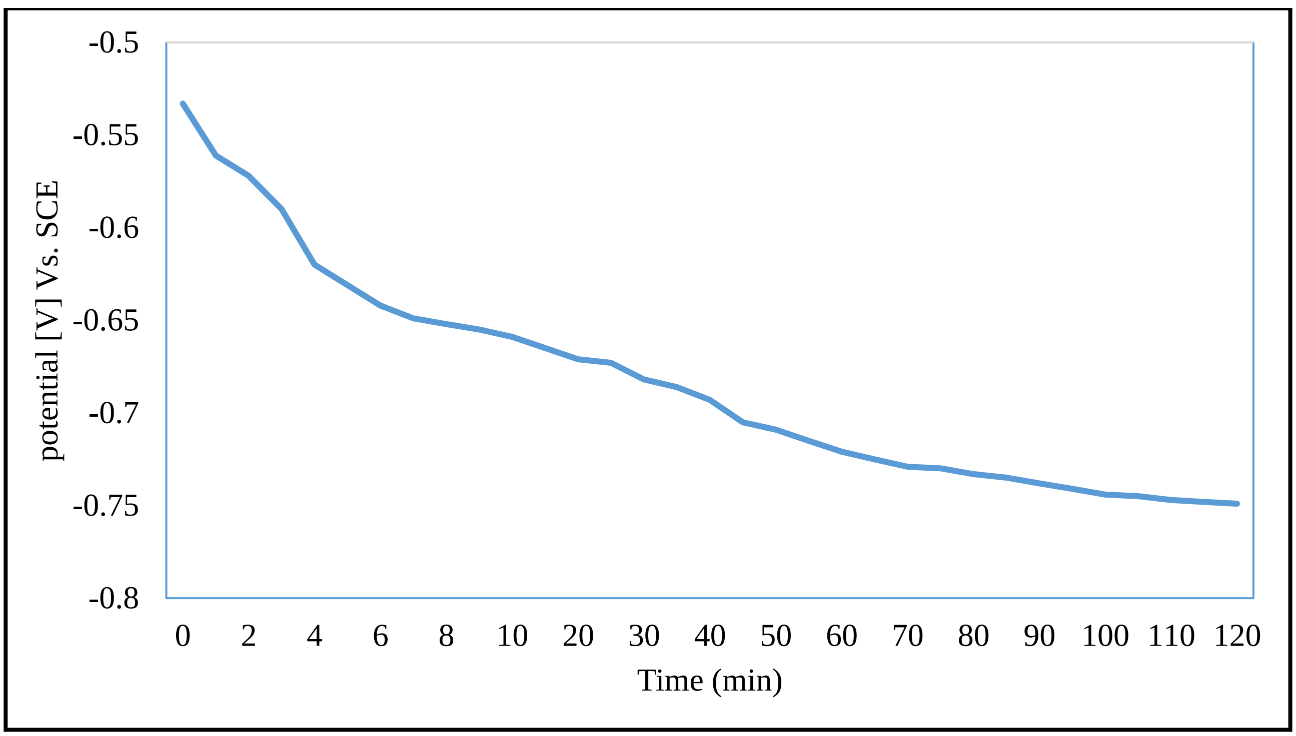

Figure (4-2) Potential of carbon steel vs. times in 10 g/L NaCl solution at T=20˚C

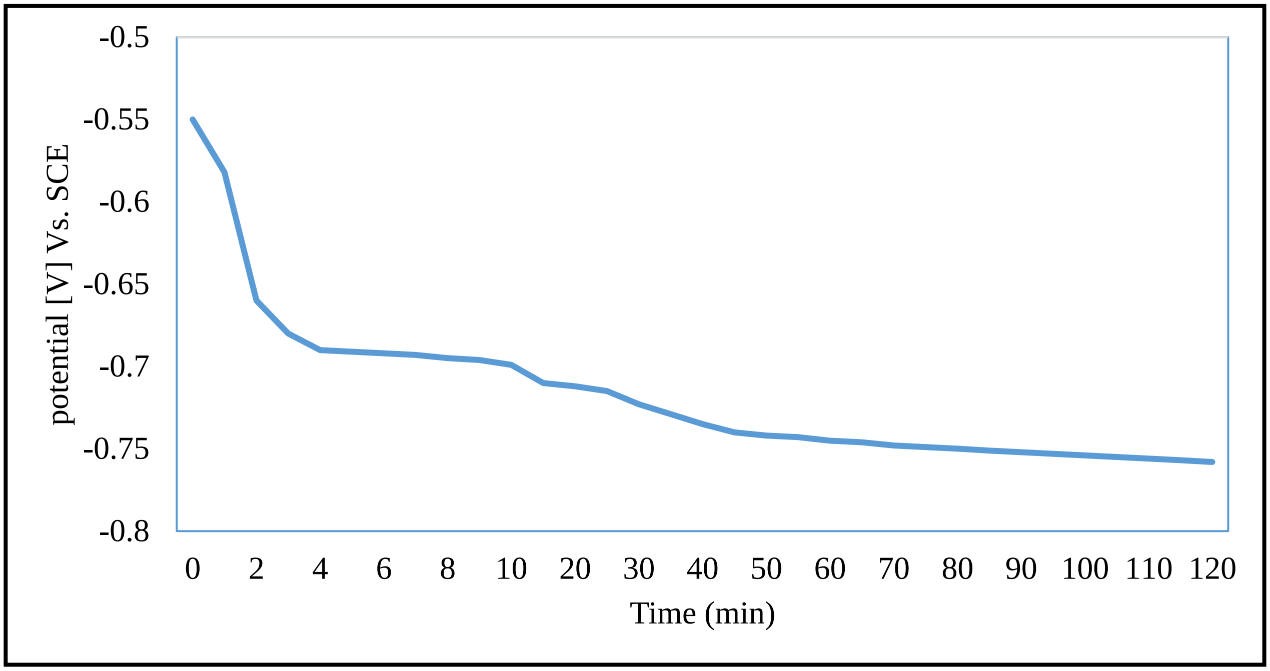

Figure (4-3) Potential of carbon steel vs. times in 20 g/L NaCl solution at T=30° C

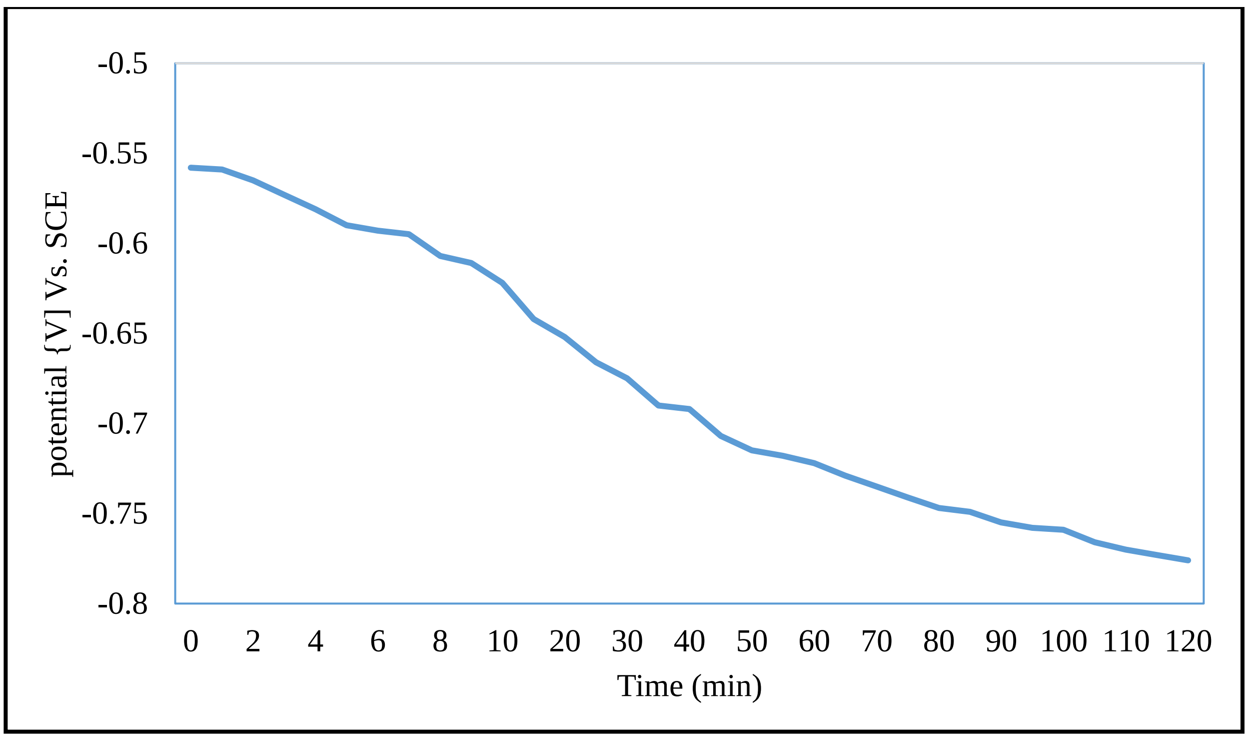

Figure (4-4) Potential of carbon steel vs. times in 35 g/L NaCl solution at T=40° C

Open circuit potentials figures 4.1 to 4.4 show that the corrosion potential Ecorr for carbon steel is more negative with increasing the NaCl solution concentrations from (5, 10, 20 and 35) g/L because increasingin the corrosion rate as tabulated in Table (4-1) reaching steady –state values after about 2hr with intubated. [80]

4.3 Potential for Cathodic Protection

By changing resistance, the most commonly known potential for cathodic protection was determined to be (-0.650V,-0.850V) at solution temperatures of (20, 30, and 40) °C, but as solution temperatures went above 40°C. A higher negative potential was necessary to protect the metal pipe. A series experiments were carried out to illustrate what value of potential is required to protect (CS) metal pipe at different temperatures and cathode-to-anode distances at various concentration of NaCl solution, (5, 10, 20, and 35)g/L such that.

As indicated in the results, the potential results in near nil weight loss under the study conditions of variable NaCl concentrations.

Additionally, as shown in figures 4.5 to 4.20, the potential is more detrimental than the corrosion potentials under all of the investigated circumstances (different temperatures and distances between cathode and anode). For these reasons, it was selected as the cathodic protection potential for carbon steel pipe.

4.4 Factors Affecting the Cathodic Protection

4.4.1. Effect of Temperature

A. On Cathodic Protection Current Density (I_{cp})

In figures 4-5,4-6 and 4-7,4-8the one can note, that the temperature affects Impressed current cathodic protection (lccp) where increase in the temperature increases cathodic protection current at different NaCl concentration (5, 10, 20 and 35) g/L and different distances (D) between the cathode and anode2,25and50cm. This is described by the anodic reaction relaxation of electron mobility, which results in an increase in conductivity as the environment resistance decreases. [81]

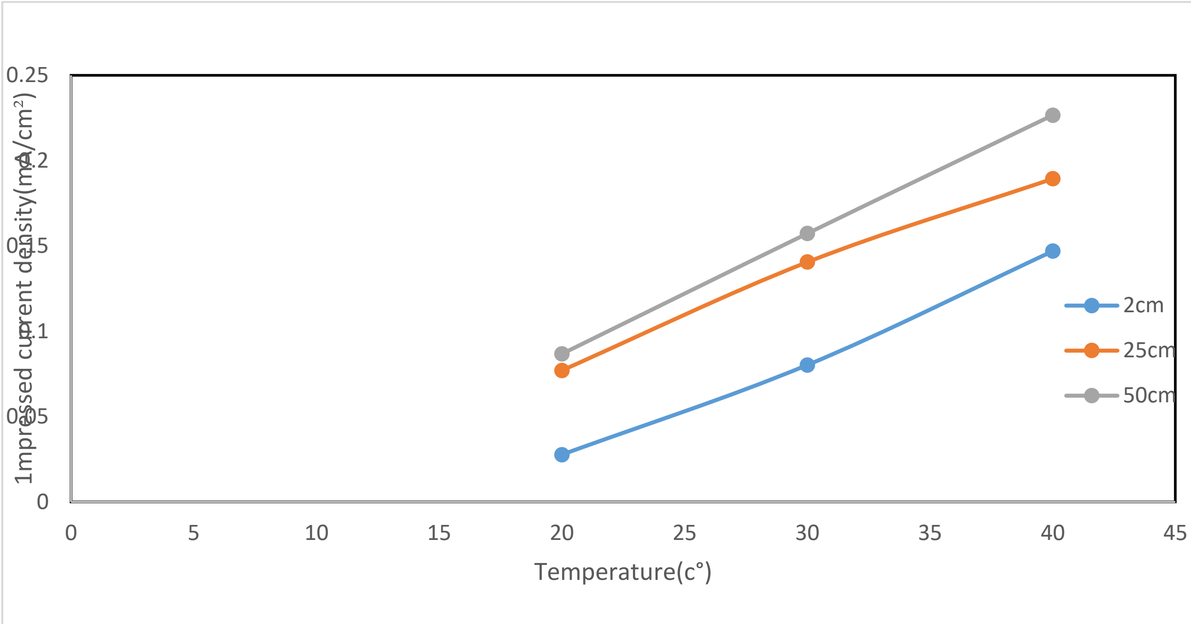

Figure (4-5) Impressed Current density vs. temperature at -0.65 V and 5g/L NaCl

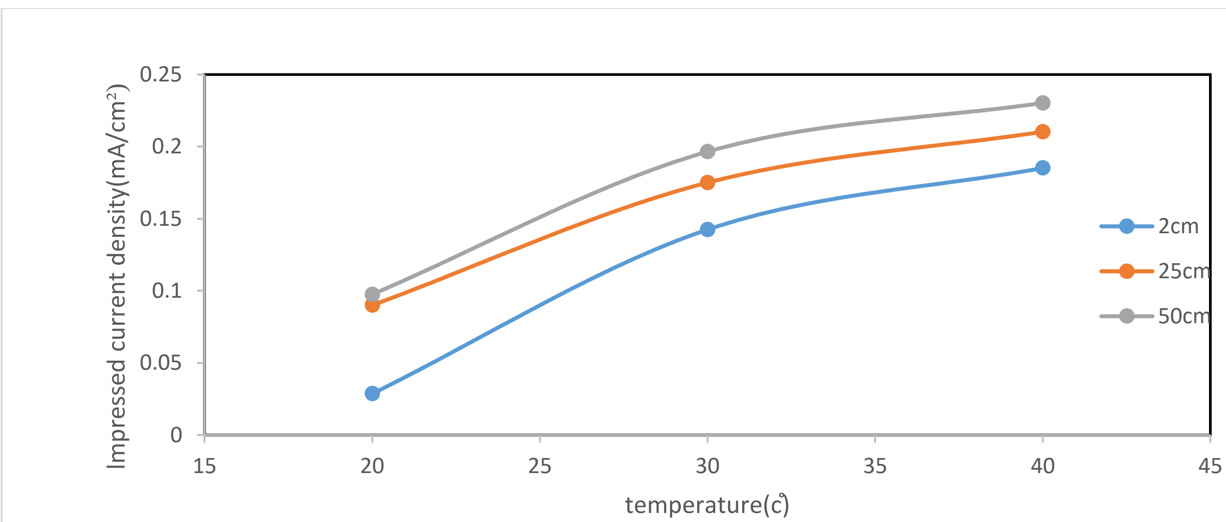

Figure (4-6) Impressed Current density vs. temperature at -0.65 V and 10 g/L NaCl

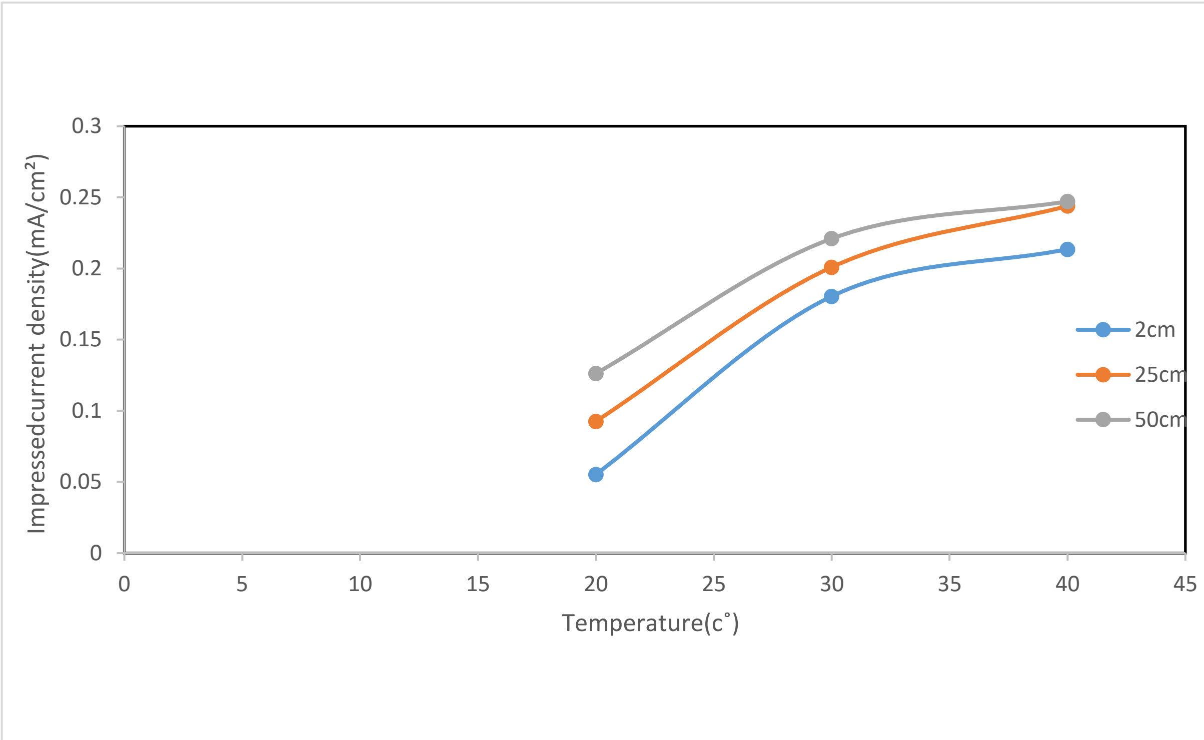

Figure (4-7) Impressed Current density vs. temperature a t-0.65 V and 20 g/L NaCl

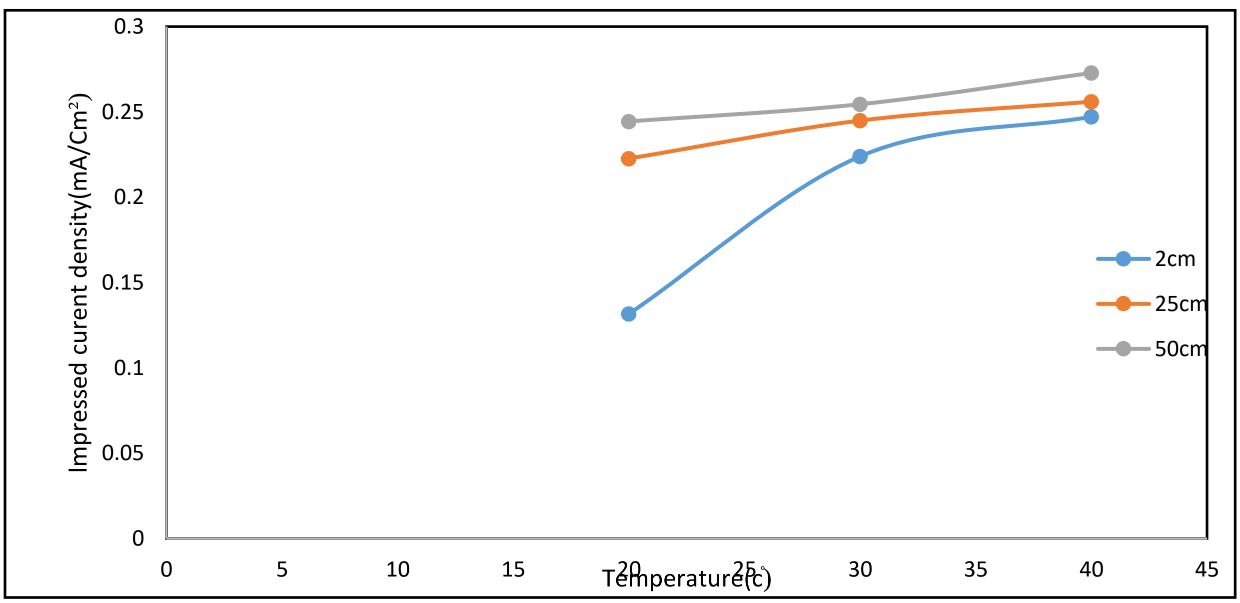

Figure (4-8) Impressed Current density vs. temperature at -0.65V and 35 g/L NaCl

B. Effect on Corrosion Rate

Figures (4-9), (4-10), and (4-11) show how temperature affects corrosion rate, with an increase in temperature increasing corrosion rate as a result of an increase in reaction kinetics.

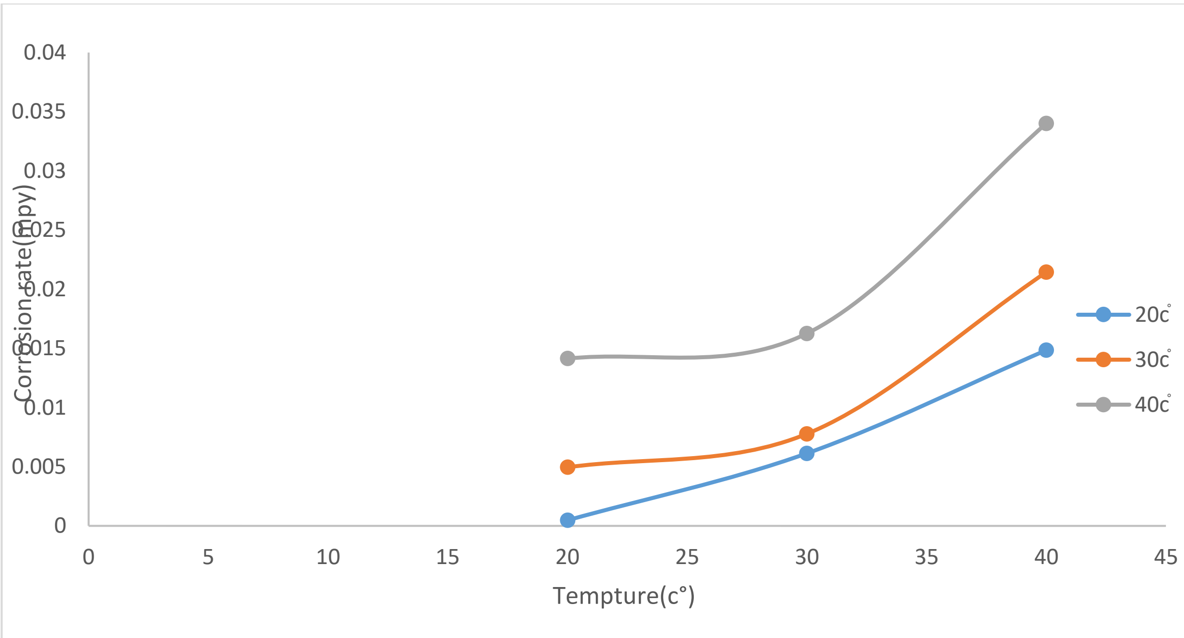

Figure (4-9) corrosion rate vs. temperature at -0.65 V and 10 g/L NaCl

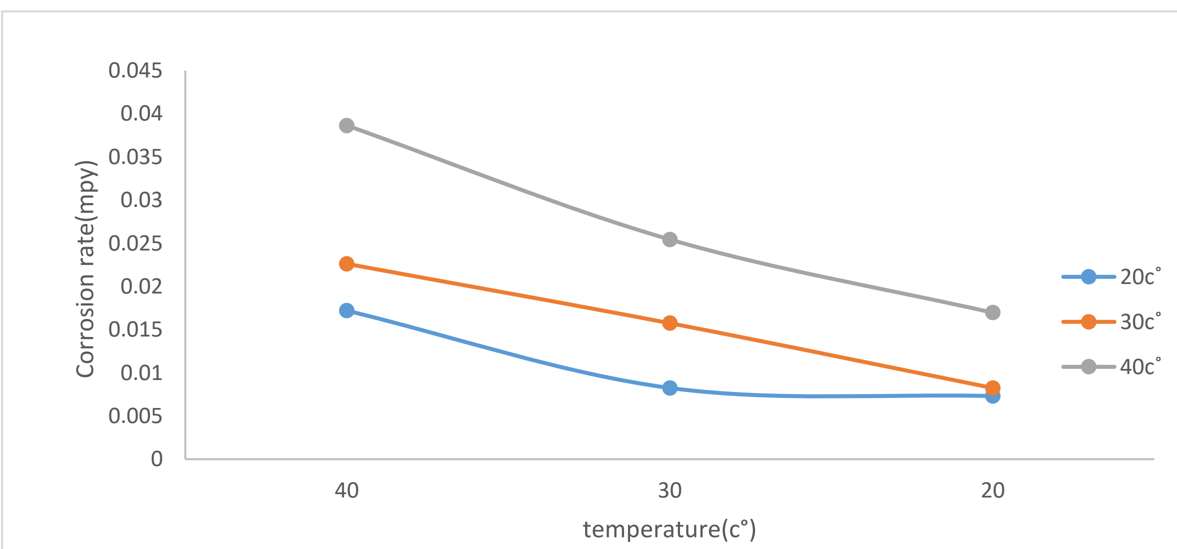

Figure (4-10) corrosion rate vs. temperature at -0.65 V and 20 g/L NaCl

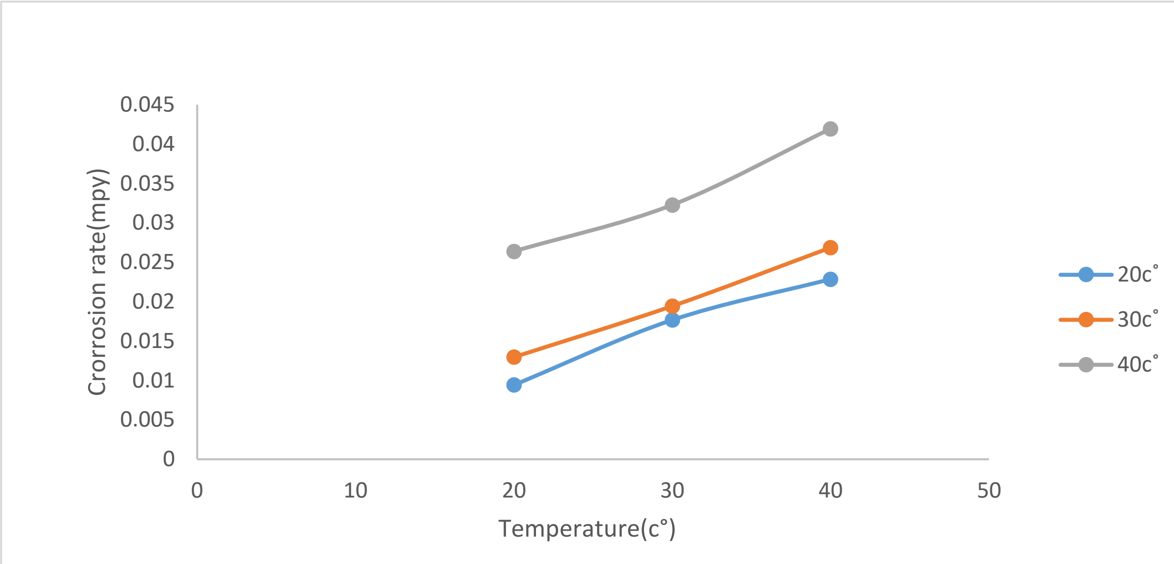

Figure (4-11) corrosion rate vs. temperature at -0.65 V and 35 g/L NaCl.

4.4.2. Effect of Concentration

A. On cathodic protection current density (I_{cp})

Experiments were conducted using different regulated cathodic currents, with potentials changing at differed NaCl concentrations for differing distance between cathode and anode as well as temperature. The bulk oxygen concentration decreases electrolyte[82]. At a constant temperature of 20° C, it shows an increase in cathodic protection current density as NaCl concentration increases over different distances between cathode and anode. The cathodic protection and current density increase as the solution increases in temperature between 30 and 40° C, as shown in the table below:

Table (4-2) Cathodic current density at different distances (x) in a variable NaCl concentrations (L=5 cm) at temperature at 20˚C.

C (g/L)	**I_{CP},x=2 cm (mA/cm²)**	**I_{CP},x=25 cm (mA/cm²)**	**I_{CP},x=50 cm (mA/cm²)**
5	0.027650225	0.077025626	0.0867
10	0.028637733	0.0900233	0.0975
20	0.055300449	0.092578877	0.1262
35	0.1316	0.222683059	0.2444

Table (4-3) Cathodic current density at different distances (x) in a variable NaCl concentrations (L=5 cm) at temperature at 30˚C.

C (g/L)	**I_{CP},x=2 cm (mA/cm²)**	**I_{CP},x=25 cm (mA/cm²)**	**I_{CP},x=50 cm (mA/cm²)**
5	0.0802	0.1405	0.157260653
10	0.142448032	0.175035797	0.196514097
20	0.180467091	0.200957883	0.221
35	0.223917444	0.24490199	0.2545

Table (4-4) Cathodic current density at different distances (x) in a variable NaCl concentrations (L=5cm) at temperature at 40˚C.

C (g/L)	**I_{CP},x=2 cm (mA/cm²)**	**I_{CP},x=25 cm (mA/cm²)**	**I_{CP},x=50 cm (mA/cm²)**
5	0.146891819	0.189354664	0.2266
10	0.185157754	0.2103	0.2303
20	0.21354861	0.2439	0.247123883
35	0.247123883	0.256	0.272799091

B. Corrosion Rate

As shown in Fig. 4-12, 4-13, 4-14 where the corrosion rate increased when the concentration of NaCl increases from (5, 10, 20, and 35) g/L NaCl while keeping all other conditions constant. It was argued that concentration as a factor plays in enhancing the rate of metal corrosion. These data were derived from the corrosion rate described in Appendix (c), which is found in studies on metals samples that involved weight loss experiment for metal specimen. This can be attributed to the increased conductivity with increase of concentration. Due to relaxation of electrons mobility. So that corrosion rate will also increase with increasing Nacl concentration under partial cathodic protection. [42]

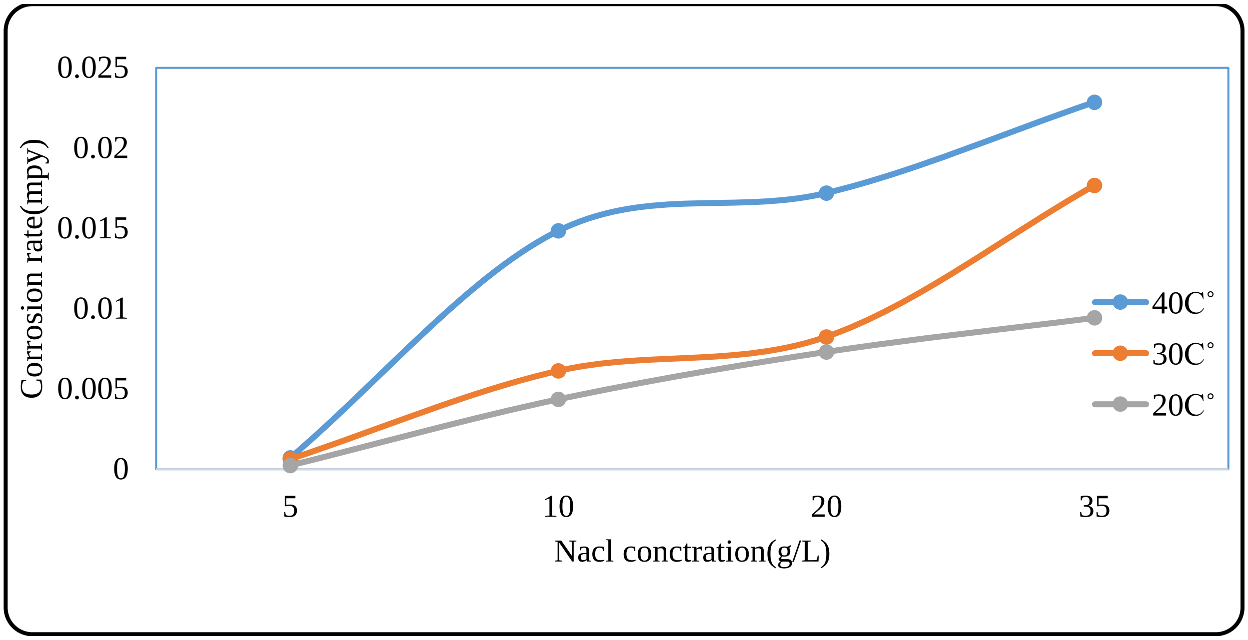

Figure (4-12) NaCl concentrations corrosion rate at distance 2 cm and different temperature.

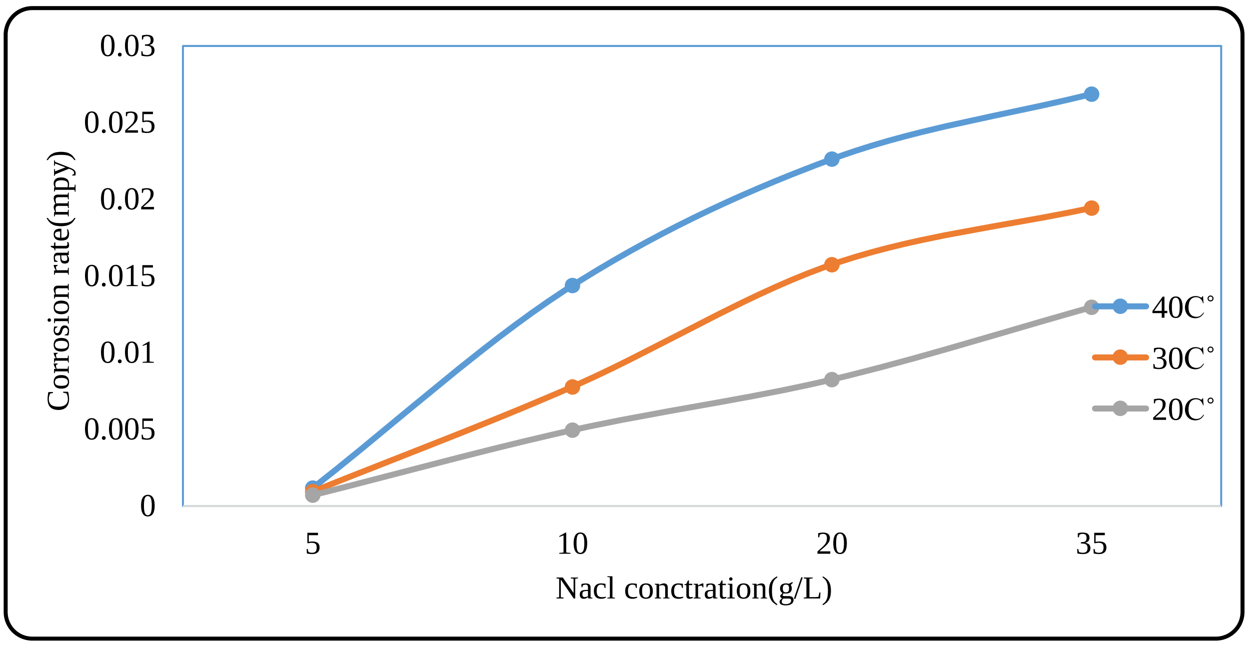

Figure (4-13) NaCl concentrations corrosion rate at distance 25 cm and different temperature.

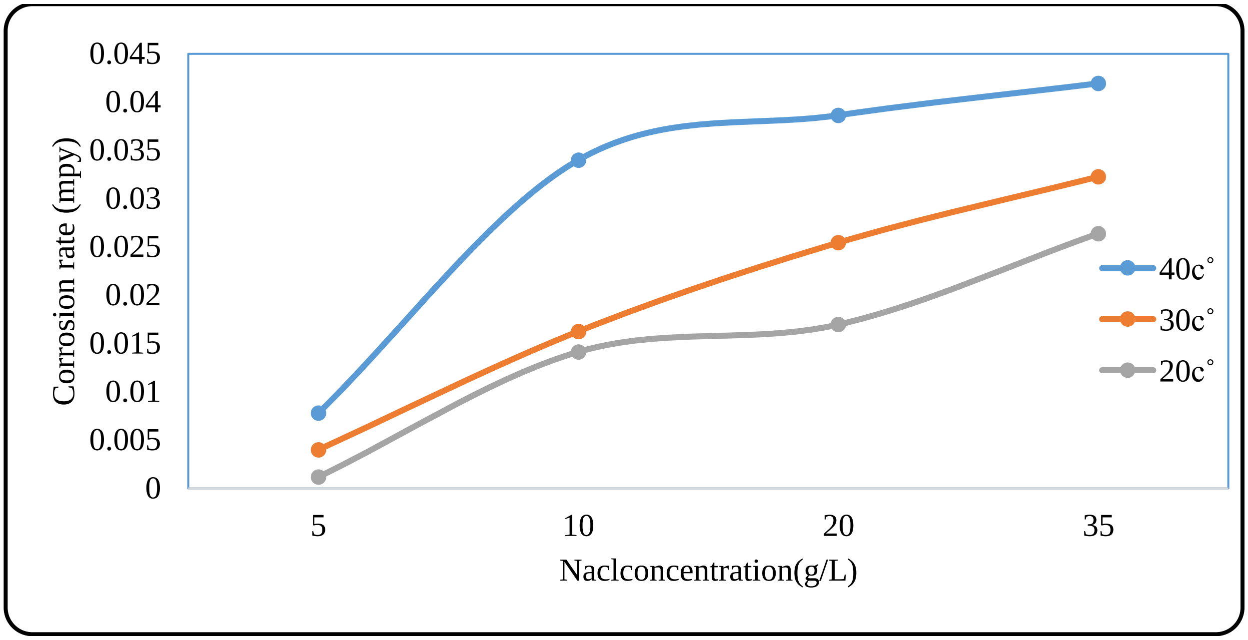

Figure (4-14) NaCl concentrations corrosion rate at distance 50 cm and different temperature.

4.4.3 Effect of Distance Between Cathode and Anode

A. on cathodic protection currented density (I_{CP})

Also shown in figures 4-15, 4-16, and 4-17 it can be seen that the cathodic protection current density increased with increasing distance between cathode and anode for different concentration .This can be attributed to increasing of electrolyte [83], decreasing conductivity of electrolyte with increasing distance cathode and anode ,so that increasing cathodic protection current density with increasing resistance of solution.

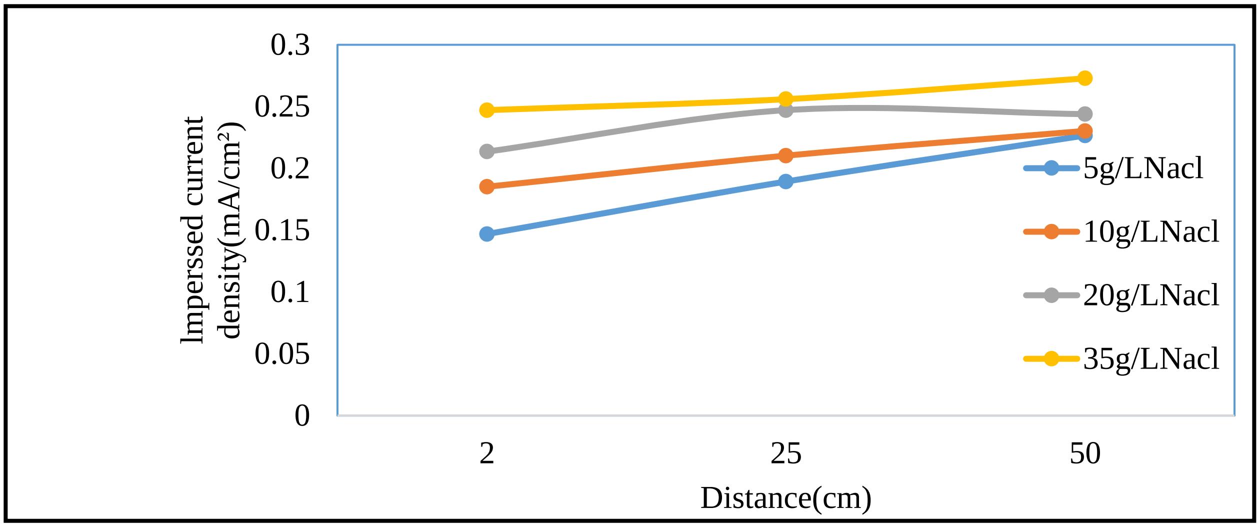

Figure (4-15) Impressed Current density vs cathode-to-anode distance at 40°C and -0.65v.

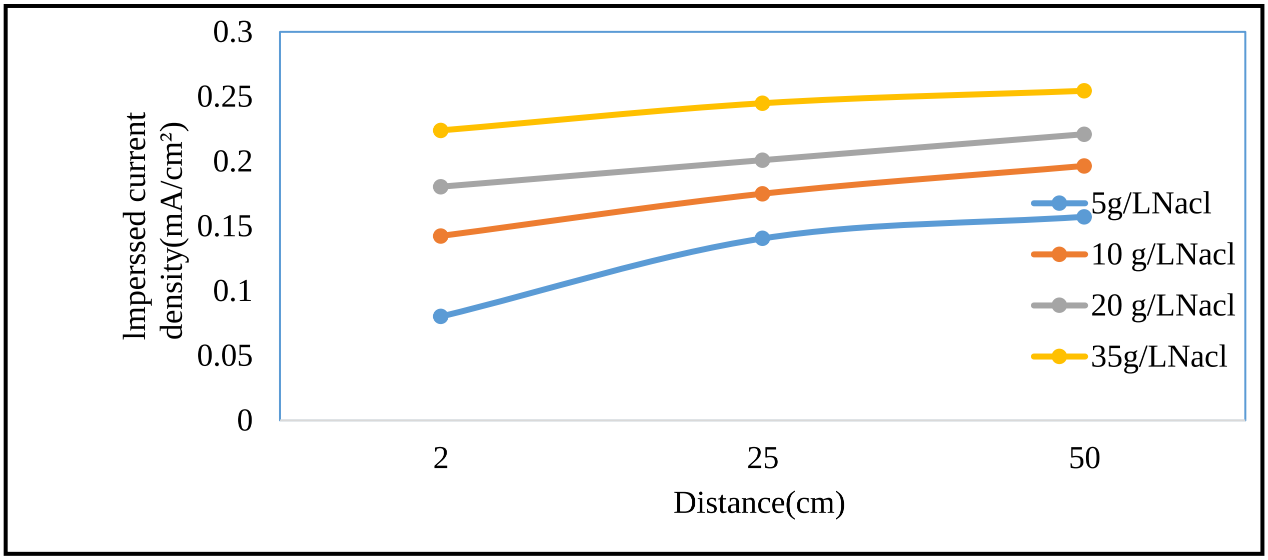

Figure (4-16) Impressed Current density vs cathode-to-anode distance at 30°C and –0.65 v.

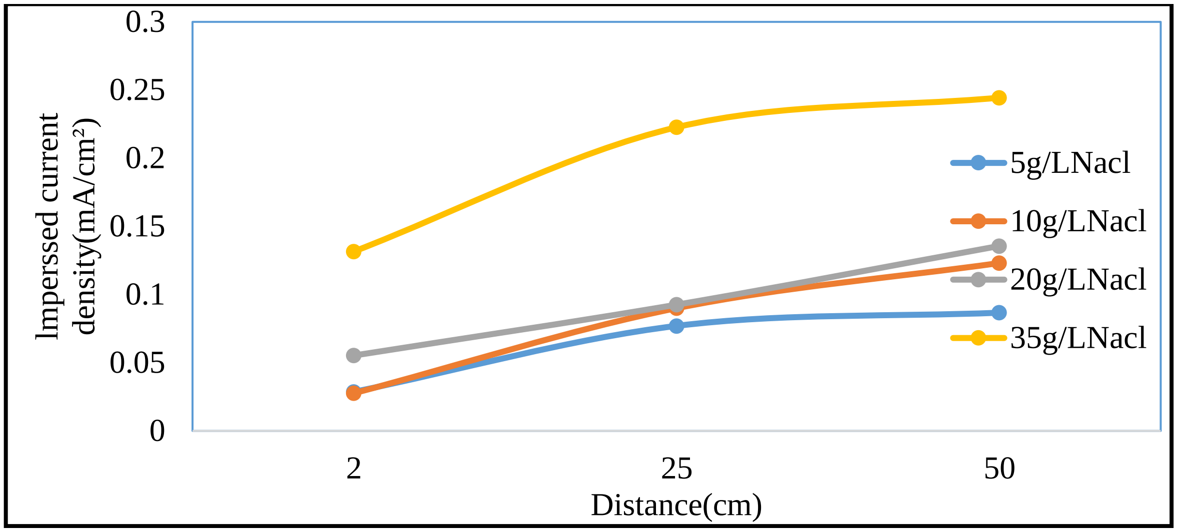

Figure (4-17) Impressed Current density vs cathode-to-anode distance at 20°C and –0.65 v.

B. The corrosion rate

The data in figure (4-18), (4-19) and (4-20) illustrate that, for almost constant cathodic current, changes between the cathode and anode is adistance have effect on the corrosion rate of heavily secured specimens, (x) and different NaCl concertation and temperature .That corrosion rate is independent upon change in x it is nearly constant at any x under approximately similar condition of partial cathodic protection.

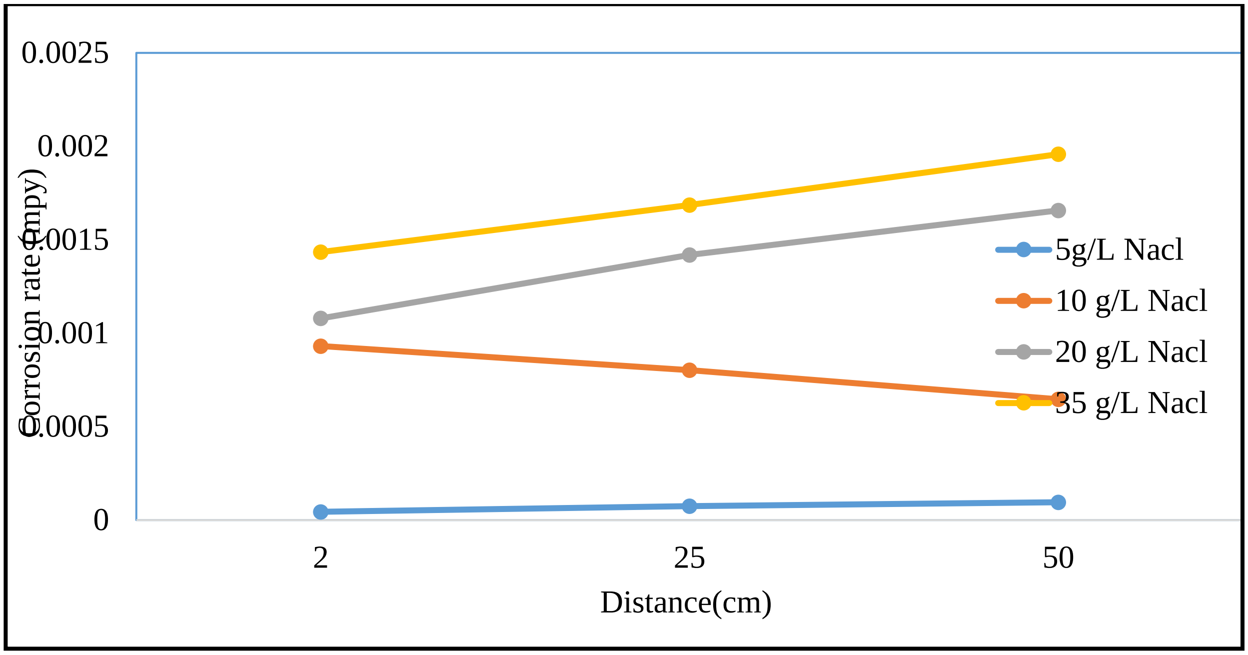

Figure (4-18) Corrosion rate vs distance between cathodic and anodicat -0.65 v at different NaCl concentration at 40° C.

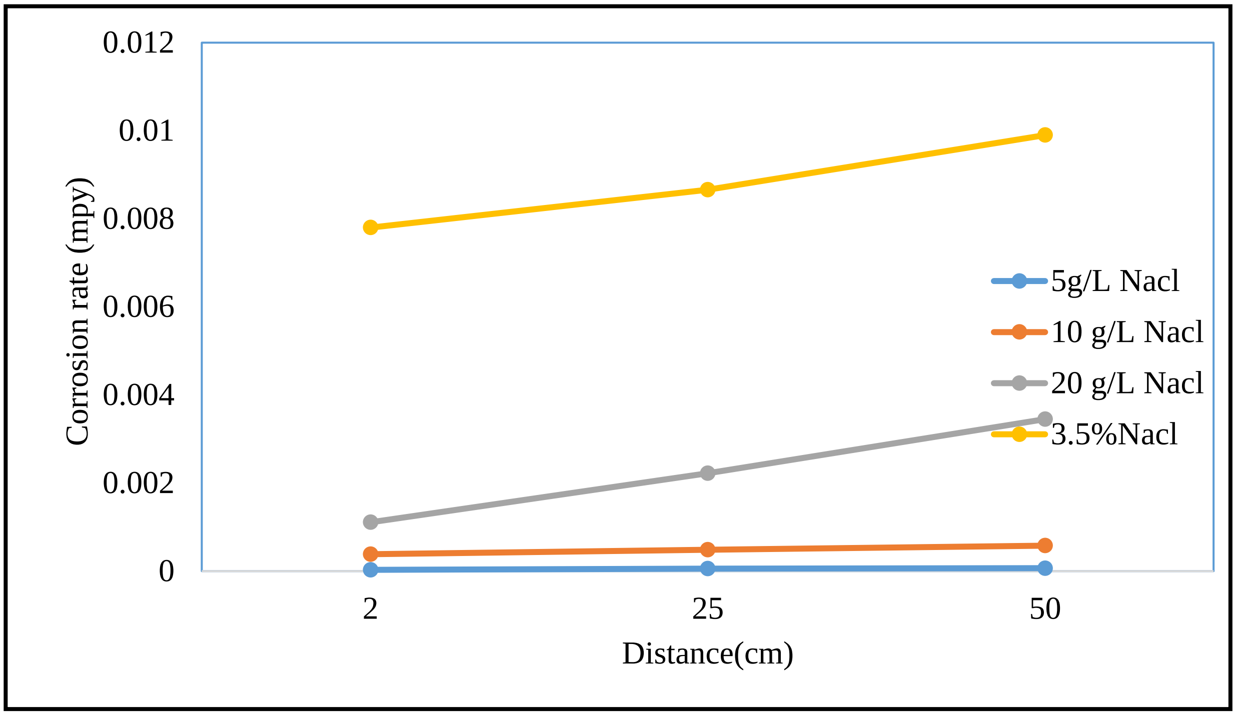

Figure (4-19) Corrosion rate vs distance between cathodic and anodic at -0.65 v at different NaCl concentration at 30° C.

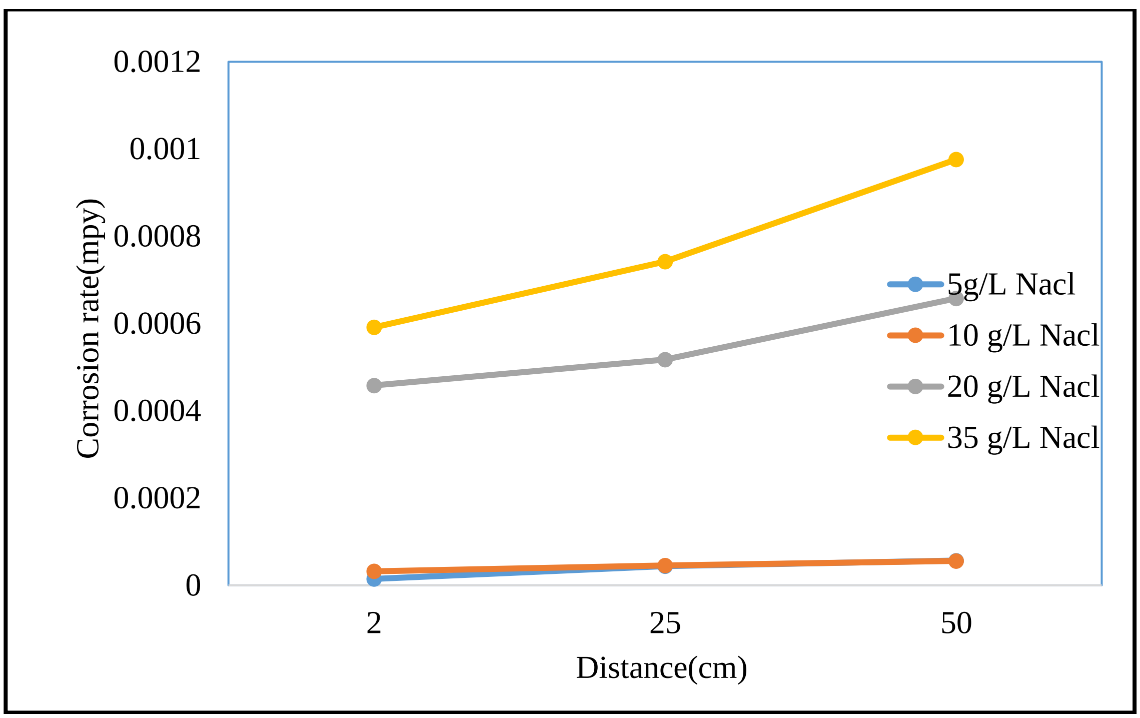

Figure (4-20) Corrosion rate vs distance between cathodic and anodic at -0.65 v at different NaCl concentration at 20C°

CHAPTER FIVE

Conclusions and Suggestions

5.1 Conclusions

The investigation results lead to the following conclusions:

1- Corrosion potential (E Potential) is more negative when NaCl concentration and temperature increasing.

2- The current density of the cathodic protection increases as temperature and. concentration of NaCl and distance between cathode and anode increases .

3- The cathodic protection potential requirement becomes more negative as the temperature increases at 20°, 30°, and 40°C.

4- The current density of cathodic protection decreases with increasing time.

5- Corrosion rate increases when increasing NaCl concentration and temperatures increase.

6- A relationship between I_{cp}, NaCl concentration, solution temperatures and the distance between cathode and anode.

5.2 Suggestions for Future Works

1) Investigating (ICCPS) with a longer time range and a longer distance between cathode and anode under different variables.

2) Using one type of bacteria and its relationship with Catholic protection.

3) Examining the effects of different coatings on (I_{cp}).

4) Instead of graphite, studying a different anode material .

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Appendix A

Properties and Equation

A-1 Properties of Specimen:

Length of specimen (L)=5 cm

Outside dimeter of specimen (dout)=2.58 cm

Specimen area(A)=2∏*d*L=40.506 cm²

A-2 The Equation:

$$\frac{mm}{y} = 1/2.47\ gmd$$

$$gmd\left(\frac{g}{m^2} * day\right) = \frac{\Delta w}{A} * t$$

$$mpy = \frac{\frac{mm}{y}}{0.0254}$$

$$id = \Delta w * z * \frac{f}{MWt} * A * t, where$$

Id=dissolution current density (A/m²)

Δw=weight loss (g)

Z=number of electrons

F=faradays number (96487 c/g. equivalents =nf (c/g.mol).

MWt=Molecular weight of metal =65.41 g/mol.

t=exposure time (s)=4 hr=0.1667 day=0.00045 =240 sec.

A=total area of metal specimen (cm^2) .

Figure A-1: chemical composition test

TÜV AUSTRIA
EN ISO 9001:2015
EN ISO 14001:2015

Ministry of Industry and Minerals
State Company for Inspection and Engineering Rehabilitation (SIER)
Engineering Insp. & lab Department

Client: وزارة التعليم العالي والبحث العلمي / جامعة بابل – كلية الهندسة / الطالبة غفران عبد الكريم عباس

Order No: 922 /2022

Tested Item: pipe

Address: Iraq- Babylon

Date of Test: 3 / 8 / 2022

Type of Test: Chemical Composition

Standard Specification: ASTM E415:2017

Test Report

Sample	C%	Si%	Mn%	P%	S%	Cr%	Mo%	Ni%	Al%	Cu%	Fe%
Pipe Ø26 mm	0.202	0.241	0.496	0.0217	0.0078	0.0124	0.0032	0.0063	0.0169	0.0041	Bal.
U ex	±0.026	±0.024	±0.069	±0.001	±0.000	±0.006	±0.000	±0.002	±0.000	±0.003	±-----

NOTE:-

- Values were calculated through three tests.
- the results of uncertainty as they are shown in the table above. the report expanded uncertainty of standard uncertainty of measurement multiplied by the coverage measurement is stated as the factor K= 2 which for a normal distribution corresponds to Confidence level of 95%.
- This test report is for the tested samples only.
- Test condition (26 ° C , 25%).
- The test report shall not be reproduced except in full without written approval of the laboratory.

مدير قسم الفحص الهندسي و المختبرات

المراجع

الفاحص

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Appendix B

Cathodic protection results

Table (B-1) cathodic protection results at 2 cm distance, 40˚C, 5 g

		at conc.= 5 gr		
temper(c̊)	**time(sec)**	**E (V)**	**Current (mA)**	**i (mA/cm²)**
40	0	-0.65	12.06	0.297733669
	15	-0.65	11.88	0.293289883
	30	-0.65	11.84	0.292302375
	45	-0.65	11.82	0.291808621
	60	-0.65	11.8	0.291314867
	75	-0.65	11.78	0.290821113
	90	-0.65	11.76	0.290327359
	105	-0.65	11.74	0.289833605
	120	-0.65	11.73	0.289586728
	135	-0.65	11.71	0.289092974
	150	-0.65	11.7	0.288846097
	165	-0.65	1.92	0.047400385
	180	-0.65	1.29	0.031847134
	195	-0.65	1.29	0.031847134
	210	-0.65	1.28	0.031600257
	225	-0.65	1.16	0.028637733
	240	-0.65	1.16	0.028637733

Table (B-2) cathodic protection results at 2 cm distance, 30˚C, 5 g

temper(c̊)	time(sec)	E (V)	Current (mA)	i (mA/cm²)
30	0	-0.65	7.28	0.17972646
	15	-0.65	6.21	0.153310621
	30	-0.65	6.18	0.15256999
	45	-0.65	6.15	0.151829359
	60	-0.65	6.12	0.151088728
	75	-0.65	6.08	0.15010122
	90	-0.65	6.05	0.149360589
	105	-0.65	5.99	0.147879327
	120	-0.65	5.95	0.146891818
	135	-0.65	5.93	0.146398064
	150	-0.65	5.89	0.145410556
	165	-0.65	5.87	0.144916802
	180	-0.65	5.86	0.144669925
	195	-0.65	5.83	0.143929294
	210	-0.65	5.81	0.14343554
	225	-0.65	5.79	0.142941786
	240	-0.65	5.77	0.142448032

Table (B-3) cathodic protection results at 2 cm distance, 20˚C, 5 g

temper(c̊)	time(sec)	E (V)	Current (mA)	i (mA/cm^2)
20	0	-0.65	6.85	0.169110749
	15	-0.65	6.76	0.166888856
	30	-0.65	6.58	0.16244507
	45	-0.65	6.47	0.159729423
	60	-0.65	6.36	0.157013776
	75	-0.65	6.33	0.156273145
	90	-0.65	6.3	0.155532514
	105	-0.65	6.25	0.154298129
	120	-0.65	6.21	0.153310621
	135	-0.65	6.18	0.15256999
	150	-0.65	6.16	0.152076236
	165	-0.65	6.13	0.151335605
	180	-0.65	6.09	0.150348097
	195	-0.65	6.03	0.148866835
	210	-0.65	6	0.148126204
	225	-0.65	5.99	0.147879327
	240	-0.65	5.95	0.146891818

Table (B-4) cathodic protection results at 2 cm distance, 40˚C ,10 g

at conc.= 10 gr		
E (V)	**Current (mA)**	**i (mA/cm²)**
-0.65	17.6	0.43450353
-0.675	17.1	0.42215968
-0.66	11.7	0.288846097
-0.678	11.7	0.288846097
-0.68	11.7	0.288846097
-0.69	11.7	0.288846097
-0.678	11.6	0.286377327
-0.666	11.6	0.286377327
-0.659	7.6	0.187626524
-0.645	7.6	0.187626524
-0.67	7.5	0.185157754
-0.658	7.5	0.185157754
-0.658	7.5	0.185157754
-0.658	7.5	0.185157754
-0.655	7.5	0.185157754
-0.645	7.5	0.185157754
-0.65	7.5	0.185157754

Table (B-5) cathodic protection results at 2 cm distance, 30˚C, 10 g

E (V)	**Current (mA)**	**i (mA/cm^2)**
-0.655	5.79	0.142941786
-0.66	5.77	0.142448032
-0.662	3.8	0.093813262
-0.666	3.79	0.093566385
-0.667	2.84	0.07011307
-0.669	2.83	0.069866193
-0.674	2.27	0.05604108
-0.675	1.62	0.039994075
-0.649	1.26	0.031106503
-0.649	1.14	0.028143979
-0.65	1.13	0.027897102
-0.651	1.13	0.027897102
-0.657	1.13	0.027897102
-0.658	1.12	0.027650225
-0.655	1.12	0.027650225
-0.65	1.12	0.027650225
-0.65	1.12	0.027650225

Table (B-6) cathodic protection results at 2 cm distance, 20˚ C,10g

E (V)	Current (mA)	i (mA/cm²)
-0.655	3.54	0.0874
-0.67	3.53	0.0871
-0.677	3.51	0.0867
-0.658	3.5	0.0864
-0.685	3.49	0.0862
-0.69	3.47	0.0857
-0.678	3.46	0.0854
-0.675	3.44	0.0849
-0.667	3.43	0.0847
-0.67	3.41	0.0842
-0.687	3.38	0.0834
-0.677	3.36	0.0830
-0.679	3.3	0.0815
-0.655	3.27	0.0807
-0.658	3.26	0.0805
-0.665	3.26	0.0805
-0.66	3.25	0.0802

Table (B-7) cathodic protection results at 2 cm distance, 40˚ C, 20 g

at conc.= 20 gr		
E (V)	**Current (mA)**	**i (mA/cm²)**
-0.65	11.42	0.281933541
-0.672	11.39	0.28119291
-0.667	11.38	0.280946033
-0.668	11.26	0.277983509
-0.655	11.2	0.276502247
-0.666	10.36	0.255764578
-0.668	9.57	0.236261295
-0.67	9.56	0.236014418
-0.655	9.47	0.233792525
-0.657	9.03	0.222929936
-0.655	9.01	0.222436182
-0.666	9	0.222189305
-0.65	8.79	0.217004888
-0.648	8.79	0.217004888
-0.658	8.79	0.217004888
-0.654	8.78	0.216758011
-0.656	8.65	0.21354861

Table (B-8) cathodic protection results at 2 cm distance, 30C° 20g

E (V)	**Current (mA)**	**i (mA/cm²)**
-0.654	7.66	0.189107787
-0.655	7.61	0.187873401
-0.671	7.59	0.187379647
-0.7	7.55	0.186392139
-0.65	7.52	0.185651508
-0.658	7.51	0.185404631
-0.667	7.51	0.185404631
-0.63	7.49	0.184910877
-0.64	7.48	0.184664
-0.625	7.45	0.183923369
-0.641	7.43	0.183429615
-0.65	7.41	0.182935861
-0.663	7.4	0.182688984
-0.667	7.35	0.181454599
-0.67	7.33	0.180960845
-0.666	7.33	0.180960845
-0.671	7.31	0.180467091

Table (B-9) cathodic protection results at 2 cm distance, 20° C, 20g

E (V)	Current (mA)	i (mA/cm²)
-0.65	2.99	0.073816225
-0.64	2.96	0.073075594
-0.632	2.95	0.072828717
-0.659	2.93	0.072334963
-0.655	2.91	0.071841209
-0.652	2.87	0.070853701
-0.654	2.85	0.070359947
-0.652	2.82	0.069619316
-0.65	2.78	0.068631808
-0.65	2.75	0.067891177
-0.65	2.72	0.067150546
-0.65	2.5	0.061719251
-0.65	2.44	0.060237989
-0.65	2.39	0.059003604
-0.65	2.25	0.055547326
-0.65	2.24	0.055300449
-0.65	2.24	0.055300449

Table (B-10) cathodic protection results at 2 cm distance, 40˚ C, 35 g

at conc.= 35 gr		
E (V)	**Current (mA)**	**i (mA/cm²)**
-0.65	11.75	0.290080482
-0.65	11.65	0.287611712
-0.65	11.5	0.283908557
-0.65	11.49	0.28366168
-0.65	11.45	0.282674172
-0.65	11.42	0.281933541
-0.65	11.4	0.281439787
-0.65	11.37	0.280699156
-0.65	11.34	0.279958525
-0.65	11.31	0.279217894
-0.65	11.28	0.278477263
-0.65	11.23	0.277242878
-0.65	11.2	0.276502247
-0.65	11.17	0.275761616
-0.65	11.12	0.274527231
-0.65	11.09	0.2737866
-0.65	11.05	0.272799091

Table (B-11) cathodic protection results at 2 cm distance, 30˚C, 35 g

E (V)	Current (mA)	i (mA/cm²)
-0.65	9.95	0.245642621
-0.65	9.89	0.244161359
-0.65	9.86	0.243420728
-0.65	9.81	0.242186343
-0.65	9.76	0.240951958
-0.65	9.65	0.238236311
-0.65	9.58	0.236508172
-0.65	9.45	0.233298771
-0.65	9.39	0.231817509
-0.65	9.32	0.230089369
-0.65	9.2	0.227126845
-0.65	9.17	0.226386214
-0.65	9.14	0.225645583
-0.65	9.12	0.225151829
-0.65	9.08	0.224164321
-0.65	9.05	0.22342369
-0.65	9.02	0.222683059

Table (B-12) cathodic protection results at 2 cm distance , 20˚C, 35 g

E (V)	**Current (mA)**	**i (mA/cm²)**
-0.65	5.55	0.137016738
-0.65	5.49	0.135535476
-0.65	5.4	0.133313583
-0.65	5.39	0.133066706
-0.65	5.35	0.132079198
-0.65	5.32	0.131338567
-0.65	5.28	0.130351059
-0.65	5.24	0.129363551
-0.65	5.2	0.128376043
-0.65	5.14	0.126894781
-0.65	5.09	0.125660396
-0.65	5.04	0.124426011
-0.65	5.02	0.123932257
-0.65	4.99	0.123191626
-0.65	4.95	0.122204118
-0.65	4.94	0.121957241
-0.65	9.92	0.24490199

Table (B-13) cathodic protection results at 25cm distance , 40˚ C, 5g

at conc.= 5 gr		
E (V)	**Current (mA)**	**i (mA/cm²)**
-0.65	9.68	0.2390
-0.65	9.58	0.2365
-0.65	8.28	0.2044
-0.65	8.25	0.2037
-0.65	8.23	0.2032
-0.65	8.2	0.2024
-0.65	7.69	0.1898
-0.65	7.66	0.1891
-0.65	7.66	0.1891
-0.65	7.18	0.1773
-0.65	7.13	0.1760
-0.65	6.62	0.1634
-0.65	6.3	0.1555
-0.65	6.2	0.1531
-0.65	6.15	0.1518
-0.65	6.13	0.1513
-0.65	5.33	0.1316

Table (B-14) cathodic protection results at 25cm distance , 30˚ C, 5g

E (V)	**Current (mA)**	**i (mA/cm²)**
-0.65	8.66	0.213795487
-0.65	8.33	0.205648546
-0.65	8.32	0.205401669
-0.65	8.32	0.205401669
-0.65	8.31	0.205154792
-0.65	8.31	0.205154792
-0.65	8.3	0.204907915
-0.65	8.21	0.202686022
-0.65	8.15	0.20120476
-0.65	7.83	0.193304696
-0.65	7.81	0.192810942
-0.65	7.79	0.192317188
-0.65	7.81	0.192810942
-0.65	7.81	0.192810942
-0.65	7.8	0.192564065
-0.65	7.79	0.192317188
-0.65	7.67	0.189354664

Table (B-15)cathodic protection results at 25cm distance , 20C˚, 5g

E (V)	Current (mA)	i (mA/cm²)
-0.65	6.72	0.165901348
-0.65	6.72	0.165901348
-0.65	6.63	0.163679455
-0.65	6.63	0.163679455
-0.65	6.59	0.162691947
-0.65	6.59	0.162691947
-0.65	6.58	0.16244507
-0.65	6.58	0.16244507
-0.65	6.58	0.16244507
-0.65	6.58	0.16244507
-0.65	6.49	0.160223177
-0.65	6.49	0.160223177
-0.65	6.48	0.1599763
-0.65	6.48	0.1599763
-0.65	6.43	0.158741915
-0.65	6.41	0.158248161
-0.65	6.37	0.157260653

Table (B-16) cathodic protection results at 25cm distance, 40˚C, 10g

at conc=10g		
E (V)	**Current (mA)**	**i (mA/cm²)**
-0.65	10.72	0.2647
-0.65	10.7	0.2642
-0.662	10.64	0.2627
-0.659	10.6	0.2617
-0.663	10.53	0.2600
-0.675	10.46	0.2582
-0.677	10.29	0.2540
-0.678	10.21	0.2521
-0.68	10.19	0.2516
-0.676	10.05	0.2481
-0.676	9.96	0.2459
-0.677	9.75	0.2407
-0.68	9.65	0.2382
-0.669	9.45	0.2333
-0.67	9.35	0.2308
-0.669	8.57	0.2116
-0.665	8.52	0.2103

Table (B-17) cathodic protection results at 25cm distance, 30˚ C, 10g

E (V)	Current (mA)	i (mA/cm²)
-0.65	9.5	0.234533156
-0.64	9.36	0.231076877
-0.653	9.34	0.230583123
-0.657	9.32	0.230089369
-0.656	6.36	0.157013776
-0.665	6.02	0.148619958
-0.676	5.45	0.134547968
-0.676	5.45	0.134547968
-0.667	5.44	0.134301091
-0.666	5.19	0.128129166
-0.656	4.97	0.122697872
-0.656	4.26	0.105169605
-0.667	3.12	0.077025626
-0.676	3.12	0.077025626
-0.666	3.12	0.077025626
-0.658	3.12	0.077025626
-0.65	3.12	0.077025626

Table (B-18) cathodic protection results at 25cm distance, 20˚C, 10g

E (V)	**Current (mA)**	**i (mA/cm²)**
-0.65	8.99	0.221942428
-0.697	8.86	0.218733027
-0.645	8.87	0.218979904
-0.667	8.77	0.216511134
-0.673	8.75	0.21601738
-0.683	8.74	0.215770503
-0.679	8.68	0.214289241
-0.68	8.59	0.212067348
-0.699	8.59	0.212067348
-0.697	8.52	0.210339209
-0.698	8.47	0.209104824
-0.679	8.46	0.208857947
-0.639	8.46	0.208857947
-0.639	8.32	0.205401669
-0.644	8.2	0.202439145
-0.642	8.14	0.200957883
-0.647	8.14	0.200957883

Table (B-19) cathodic protection results at 25cm distance, 40˚C, 20g.

at conc =20g		
E (V)	**Current (mA)**	**i (mA/cm²)**
-0.65	10.99	0.271317829
-0.65	10.98	0.271070952
-0.662	11.6	0.286377327
-0.659	11.2	0.276502247
-0.663	11	0.271564706
-0.675	10.71	0.264405273
-0.677	10.65	0.262924011
-0.678	10.53	0.259961487
-0.68	10.44	0.257739594
-0.676	10.42	0.25724584
-0.676	10.06	0.248358268
-0.677	10.02	0.24737076
-0.68	10.02	0.24737076
-0.669	10.01	0.247123883
-0.67	9.82	0.24243322
-0.669	9.7	0.239470696
-0.655	9.07	0.223917444

Table (B-20) cathodic protection results at 25cm distance, 30˚ C, 20g

E (V)	**Current (mA)**	**i (mA/cm²)**
-0.655	10.92	0.26958969
-0.676	10.87	0.268355305
-0.628	10.91	0.269342813
-0.63	10.91	0.269342813
-0.636	10.91	0.269342813
-0.645	10.91	0.269342813
-0.62	10.91	0.269342813
-0.659	10.91	0.269342813
-0.671	10.89	0.268849059
-0.671	10.83	0.267367797
-0.666	10.06	0.248358268
-0.655	10.04	0.247864514
-0.656	10.05	0.248111391
-0.667	10.06	0.248358268
-0.66	10.04	0.247864514
-0.667	10.02	0.24737076
-0.678	10.01	0.247123883

Table (B-21) cathodic protection results at 25cm distance, 20˚C, 20g

E (V)	Current (mA)	i (mA/cm²)
-0.65	10.43	0.257492717
-0.655	9.51	0.234780033
-0.642	5.55	0.137016738
-0.661	5.55	0.137016738
-0.669	5.54	0.136769861
-0.675	5.53	0.136522984
-0.681	5.52	0.136276107
-0.647	5.51	0.13602923
-0.688	5.25	0.129610428
-0.665	5.24	0.129363551
-0.665	3.76	0.092825754
-0.658	3.76	0.092825754
-0.645	3.75	0.092578877
-0.657	3.75	0.092578877
-0.659	3.75	0.092578877
-0.664	3.75	0.092578877
-0.667	3.75	0.092578877

Table (B-22) cathodic protection results at 25cm distance, 40˚ C, 35g

at conc.= 35 gr		
E (V)	**Current (mA)**	**i (mA/cm²)**
-0.65	10.5	0.259220856
-0.65	10.35	0.255517701
-0.65	10.31	0.254530193
-0.65	10.12	0.24983953
-0.65	10.11	0.249592653
-0.65	9.71	0.239717573
-0.65	9.33	0.230336246
-0.65	9.27	0.228854984
-0.65	8.7	0.214782995
-0.65	8.05	0.19873599
-0.65	7.62	0.188120278
-0.65	7.58	0.18713277
-0.65	7.46	0.184170246
-0.65	7.16	0.176763936
-0.65	7.12	0.175776428
-0.65	7.1	0.175282674
-0.65	7.09	0.175035797

Table (B-23) cathodic protection results at 25cm distance, 30˚ C, 35g

E (V)	**Current (mA)**	**i (mA/cm²)**
-0.65	10.92	0.26958969
-0.65	10.87	0.268355305
-0.65	10.91	0.269342813
-0.65	10.91	0.269342813
-0.65	10.91	0.269342813
-0.65	10.91	0.269342813
-0.65	10.91	0.269342813
-0.65	10.91	0.269342813
-0.65	10.89	0.268849059
-0.65	10.83	0.267367797
-0.65	10.06	0.248358268
-0.65	10.04	0.247864514
-0.65	10.05	0.248111391
-0.65	10.06	0.248358268
-0.65	10.04	0.247864514
-0.65	10.02	0.24737076
-0.65	10.01	0.247123883

Table (B-24) cathodic protection results at 25cm distance, 20˚ C, 35g

E (V)	**Current (mA)**	**i (mA/cm²)**
-0.65	10.69	0.263911519
-0.65	10.63	0.262430257
-0.65	10.46	0.258233348
-0.65	10.46	0.258233348
-0.65	10.39	0.256505209
-0.65	10.1	0.249345776
-0.65	9.47	0.233792525
-0.65	5.25	0.129610428
-0.65	5.22	0.128869797
-0.65	4.79	0.118254086
-0.65	4.79	0.118254086
-0.65	4.79	0.118254086
-0.65	4.79	0.118254086
-0.65	4.76	0.117513455
-0.65	4.75	0.117266578
-0.65	3.68	0.090850738
-0.65	3.67	0.090603861

Table (B-25) cathodic protection results at 50cm distance, 40˚ C, 5g

at conc.= 5 gr		
E (V)	**Current (mA)**	**i (mA/cm^2)**
-0.65	10.75	0.2654
-0.65	10.73	0.2649
-0.65	10.64	0.2627
-0.65	10.56	0.2607
-0.65	10.54	0.2602
-0.65	10.51	0.2595
-0.65	10.45	0.2580
-0.65	10.33	0.2550
-0.65	10.31	0.2545
-0.65	10.22	0.2523
-0.65	10.06	0.2484
-0.65	9.96	0.2459
-0.65	9.95	0.2456
-0.65	9.95	0.2456
-0.65	9.9	0.2444
-0.65	9.88	0.2439
-0.65	9.88	0.2439

Table(B-26)cathodic protection results at 50cm distance, 30˚ C, 5g.

E (V)	Current (mA)	i (mA/cm^2)
-0.65	9.22	0.2276
-0.65	9.21	0.2274
-0.65	9.2	0.2271
-0.65	9.18	0.2266
-0.65	9.17	0.2264
-0.65	9.16	0.2261
-0.65	9.14	0.2256
-0.65	9.12	0.2252
-0.65	9.11	0.2249
-0.65	9.09	0.2244
-0.65	9.07	0.2239
-0.65	9.05	0.2234
-0.65	9.03	0.2229
-0.65	9.01	0.2224
-0.65	8.99	0.2219
-0.65	8.97	0.2214
-0.65	8.95	0.2210

Table (B-27) cathodic protection results at 50cm distance, 20˚ C, 5g

E (V)	**Current (mA)**	**i (mA/cm^2)**
-0.65	4.98	0.1229
-0.65	4.97	0.1227
-0.65	3.95	0.0975
-0.65	3.53	0.0871
-0.65	3.52	0.0869
-0.65	3.52	0.0869
-0.65	3..52	0.0869
-0.65	3.52	0.0869
-0.65	3.52	0.0869
-0.65	3.52	0.0869
-0.65	3.52	0.0869
-0.65	3.52	0.0869
-0.65	3.52	0.0869
-0.65	3.52	0.0869
-0.65	3.51	0.0867
-0.65	3.51	0.0867
-0.65	3.51	0.0867

Table (B-28) cathodic protection results at 50cm distance, 40˚ C, 10g

at conc.= 10 gr		
E (V)	**Current (mA)**	**i (mA/cm²)**
-0.65	10.25	0.2530
-0.65	8.77	0.2165
-0.65	4.35	0.1074
-0.65	4.2	0.1037
-0.65	4.19	0.1034
-0.65	4.16	0.1027
-0.65	4.16	0.1027
-0.65	4.13	0.1020
-0.65	4.13	0.1020
-0.65	4.13	0.1020
-0.65	4.12	0.1017
-0.65	4.12	0.1017
-0.65	4.09	0.1010
-0.65	4.07	0.1005
-0.65	3.98	0.0983
-0.65	3.98	0.0983
-0.65	3.95	0.0975

Table (B-29) cathodic protection results at 50cm distance, 30˚ C, 10g

E (V)	Current (mA)	i (mA/cm^2)
-0.65	10.23	0.2526
-0.65	10.21	0.2521
-0.65	10.13	0.2501
-0.65	9.96	0.2459
-0.65	9.95	0.2456
-0.65	9.93	0.2451
-0.65	9.91	0.2447
-0.65	9.89	0.2442
-0.65	9.87	0.2437
-0.65	9.25	0.2284
-0.65	9.24	0.2281
-0.65	9.22	0.2276
-0.65	9.21	0.2274
-0.65	9.2	0.2271
-0.65	9.19	0.2269
-0.65	9.18	0.2266
-0.65	9.18	0.2266

Table (B-30) cathodic protection results at 50cm distance, 20° C, 10g.

E (V)	**Current (mA)**	**i (mA/cm²)**
-0.65	9.66	0.238483188
-0.65	9.65	0.238236311
-0.65	9.43	0.232805017
-0.65	9.19	0.226879968
-0.65	9.09	0.224411198
-0.65	9.06	0.223670567
-0.65	8.96	0.221201797
-0.65	8.95	0.22095492
-0.65	8.94	0.220708043
-0.65	8.93	0.220461166
-0.65	8.92	0.220214289
-0.65	8.08	0.199476621
-0.65	8.06	0.198982867
-0.65	8.03	0.198242236
-0.65	8	0.197501605
-0.65	7.98	0.197007851
-0.65	7.96	0.196514097

Table (B-31) cathodic protection results at 50cm distance, 40° C, 20g

at conc.= 20 gr		
E (V)	**Current (mA)**	**i (mA/cm²)**
-0.65	11.12	0.2745
-0.65	11.7	0.2888
-0.65	10.94	0.2701
-0.65	10.75	0.2654
-0.65	8.88	0.2192
-0.65	8.19	0.2022
-0.65	8.14	0.2010
-0.65	7.57	0.1869
-0.65	7.2	0.1778
-0.65	7.13	0.1760
-0.65	7.12	0.1758
-0.65	7.09	0.1750
-0.65	5.73	0.1415
-0.65	5.72	0.1412
-0.65	5.71	0.1410
-0.65	5.7	0.1407
-0.65	5.69	0.1405

Table (B-33) cathodic protection results at 50cm distance, 30° C, 20g

E (V)	Current (mA)	i (mA/cm^2)
-0.65	10.21	0.2521
-0.65	9.51	0.2348
-0.65	9.43	0.2328
-0.65	6.73	0.1661
-0.65	5.9	0.1457
-0.65	5.65	0.1395
-0.65	5.25	0.1296
-0.65	5.24	0.1294
-0.65	5.23	0.1291
-0.65	5.23	0.1291
-0.65	5.22	0.1289
-0.65	5.21	0.1286
-0.65	5.16	0.1274
-0.65	5.13	0.1266
-0.65	5.13	0.1266
-0.65	5.12	0.1264
-0.65	5.11	0.1262

Table (B-34) cathodic protection results at 50cm distance, 20˚ C, 20g

E (V)	**Current (mA)**	**i (mA/cm^2)**
-0.65	9.9	0.2444
-0.65	9.87	0.2437
-0.65	9.84	0.2429
-0.65	9.83	0.2427
-0.65	9.82	0.2424
-0.65	9.74	0.2405
-0.65	9.74	0.2405
-0.65	9.65	0.2382
-0.65	9.57	0.2363
-0.65	9.56	0.2360
-0.65	9.54	0.2355
-0.65	9.5	0.2345
-0.65	9.49	0.2343
-0.65	9.44	0.2331
-0.65	9.42	0.2326
-0.65	9.4	0.2321
-0.65	9.33	0.2303

Table (B-35) cathodic protection results at 50cm distance, 40˚ C, 35g

at conc.= 35 gr		
E (V)	**Current (mA)**	**i (mA/cm^2)**
-0.65	10.98	0.2711
-0.689	10.96	0.2706
-0.677	10.94	0.2701
-0.684	10.92	0.2696
-0.654	10.91	0.2693
-0.693	10.89	0.2688
-0.678	10.87	0.2684
-0.656	10.83	0.2674
-0.666	10.81	0.2669
-0.657	10.77	0.2659
-0.643	10.71	0.2644
-0.653	10.66	0.2632
-0.657	10.54	0.2602
-0.648	10.45	0.2580
-0.653	10.33	0.2550
-0.649	10.32	0.2548
-0.658	10.31	0.2545

Table (B-36) cathodic protection results at 50cm distance, 30˚ C, 35g

E (V)	Current (mA)	i (mA/cm²)
-0.65	10.9	0.2691
-0.65	10.88	0.2686
-0.667	10.85	0.2679
-0.654	10.81	0.2669
-0.67	10.75	0.2654
-0.655	10.74	0.2651
-0.675	10.72	0.2647
-0.648	10.7	0.2642
-0.685	10.6	0.2617
-0.659	10.5	0.2592
-0.678	10.47	0.2585
-0.666	10.41	0.2570
-0.656	10.4	0.2568
-0.658	10.39	0.2565
-0.668	10.37	0.2560
-0.63	10.37	0.2560
-0.63	10.37	0.2560

Table (B-37) cathodic protection results at 50cm distance, 20˚ C, 35g

E (V)	**Current (mA)**	**i (mA/cm²)**
-0.65	10.4	0.2568
-0.654	10.38	0.2563
-0.645	10.35	0.2555
-0.636	10.33	0.2550
-0.639	10.32	0.2548
-0.641	10.32	0.2548
-0.642	10.25	0.2530
-0.642	10.23	0.2526
-0.642	10.22	0.2523
-0.645	10.21	0.2521
-0.645	10.2	0.2518
-0.648	10.1	0.2493
-0.647	10.1	0.2493
-0.647	10.01	0.2471
-0.649	9.92	0.2449
-0.642	9.91	0.2447
-0.643	9.9	0.2444

Appendix C

Table (c-1) effect of impressed current density on corrosion rate (by weight loss) for metal tube specimen length (L)=5 cm, anddistance cathode and anode 2 cm .

0	at conc.= 5 gr				
temper(c̊)	**Δ w**	**ID**	**CR**		
			(gmd)	**(mm/y)**	**(mpy)**
40	0.0003	5163.168	4.43492E-05	1.79551E-05	0.000706895
temper(c̊)	**Δ w**	**ID**	**CR**		
			(gmd)	**(mm/y)**	**(mpy)**
30	0.000268	4612.43008	3.96186E-05	1.60399E-05	0.000631493
temper(c̊)	**Δ w**	**ID**	**CR**		
			(gmd)	**(mm/y)**	**(mpy)**
20	0.0001	172.1056	1.47831E-05	5.98504E-06	0.000235632

Table (c-2) effect of impressed current density on corrosion rate (by weight loss) for metal tube specimen length (L)=5 cm, anddistance cathode and anode 25cm

0	at conc.= 5 gr				
temper(c̊)	**Δ w**	**ID**	**CR**		
			(gmd)	**(mm/y)**	**(mpy)**
40	0.0005	8605.28	7.39153E-05	2.99252E-05	0.0012
temper(c̊)		**ID**	**CR**		

	Δ w		(gmd)	(mm/y)	(mpy)
30	0.0004	688.4224	5.91322E-05	2.39402E-05	0.000942526
temper(c̊)	**Δ w**	**ID**	**CR**		
			(gmd)	**(mm/y)**	**(mpy)**
20	0.0003	5163.1698	4.43492E-05	1.79551E-05	0.000706895

Table (c-3) effect of impressed current density on corrosion rate (by weight loss) for metal tube specimen length (L)=5 cm, anddistance cathode and anode 50cm

0	at conc.= 5 gr				
temper(c̊)	**Δ w**	**ID**	**CR**		
			(gmd)	**(mm/y)**	**(mpy)**
40	0.0033	5679.4848	0.000488874	0.000197925	0.0078
temper(c̊)	**Δ w**	**ID**			
			(gmd)	**(mm/y)**	**(mpy)**
30	0.0017	2925.7952	0.000251293	0.000101738	0.0040
temper(c̊)	**Δ w**	**ID**	**CR**		
			(gmd)	**(mm/y)**	**(mpy)**
20	0.0005	860.528	7.40719E-05	2.99886E-05	0.0012

Table (c-4) effect of impressed current density on corrosion rate (by weight loss) for metal tube specimen length (L)=5 cm, anddistance cathode and anode 2 cm

at conc.= 10 gr				
Δ w	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**

0.0063	108426.528	0.000931332	0.000377058	0.014844787
∆ w	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.0026	44747.456	0.000384359	0.000155611	0.006126421
∆ w	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.0002	344.2112	2.96E-05	1.20E-05	4.71E-04

Table (c-5) effect of impressed current density on corrosion rate (by weight loss) for metal tube specimen length (L)=5cm, anddistance cathode and anode 25 cm

at conc.= 10 gr				
∆ w	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.0061	10498.4416	0.000901766	0.000365088	0.0144
∆ w	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.0033	567948.5922	0.000487841	0.000197506	0.007775841
∆ w	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.0021	36142.176	0.000310444	0.000125686	0.004948263

Table (c-6) effect of impressed current density on corrosion rate (by weight loss) for metal tube specimen length (L)=5 cm, anddistance cathode and anode 50 cm

at conc.= 10 gr				
Δ w	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.0144	24783.2064	0.00213327	0.000863672	0.0340
Δ w	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.0069	11875.2864	0.001019953	0.000412936	0.0163
Δ w	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.006	10326.336	0.000886915	0.000359075	0.0141

Table (c-7) effect of impressed current density on corrosion rate (by weight loss) for metal tube specimen length (L)=5 cm, anddistance cathode and anode 2 cm

at conc.= 20 gr				
Δ w	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.0073	125637.088	0.001079163	0.000436908	0.017201106
Δ w	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.0035	60236.96	0.000517407	0.000209476	0.008247105
Δ w	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.0031	53352.736	0.000458275	0.000185536	0.007304579

Table (c-8) effect of impressed current density on corrosion rate (by weight loss) for metal tube specimen length (L)=5 cm, anddistance cathode and anode 25cm

at conc.= 20 gr				
Δ w	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.0096	165221.376	0.001419173	0.000574564	0.0226
Δ w	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.004	688422.412	0.00988	0.004	0.157480315
Δ w	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.0035	602369.6105	0.000517407	0.000209476	0.008247105

Table (c-9) effect of impressed current density on corrosion rate (by weight loss) for metal tube specimen length (L)=5 cm, anddistance cathode and anode 50cm

at conc.= 20 gr				
Δ w	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.0164	28225.3184	0.002424235	0.000981472	0.0386
Δ w	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.0108	18587.4048	0.001596448	0.000646335	0.0254

Δ **w**	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.0072	12391.6032	0.001064298	0.00043089	0.0170

Table (c-10) effect of impressed current density on corrosion rate (by weight loss) for metal tube specimen length (L)=5 cm, anddistance cathode and anode 2 cm

at conc.= 35 gr				
Δ **w**	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.0097	166942.432	0.001433956	0.000580549	0.022856264
Δ **w**	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.0075	129.075	0.001108729	0.000448878	0.017672369
Δ **w**	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.004	68842.24	0.000591322	0.000239402	0.009425263

Table (c-11) effect of impressed current density on corrosion rate (by weight loss) for metal tube specimen length (L)=5 cm, anddistance cathode and anode 25cm

at conc.= 35 gr				
Δ **w**	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**

0.0114	196200.384	0.001685268	0.000682295	0.0269
Δ w	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.006	103263.36	0.000886983	0.000359103	0.014137895
Δ w	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.0055	94658.08	0.000813068	0.000329177	0.012959737

Table (c-12) effect of impressed current density on corrosion rate (by weight loss) for metal tube specimen length (L)=5 cm, anddistance cathode and anode 50cm

at conc.= 35 gr				
Δ w	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.0178	30634.7968	0.002631182	0.001065256	0.0419
Δ w	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.0137	23578.4672	0.002025123	0.000819888	0.0323
Δ w	**ID**	**CR**		
		(gmd)	**(mm/y)**	**(mpy)**
0.0112	19275.8272	0.001655575	0.000670273	0.0264

الملخص

تمت الدراسة بإجراء تصميم منظومة حماية كاثودية بطريقة التيار المسلط لحماية أنبوب الفولاذ الكربوني لاجل دراسة العوامل المختلفة التي تؤثر على التيار المسلط الذي من شأنه أن يحمي بالكامل او جزء من عينة المعدن الأنبوبي (الكاثود) باستخدام قطب الجرافيت كأنود.

استخدم الوزن كمؤشر أداء لإجراء الحماية الكاثودية. تم اختبار ثلاثة متغيرات رئيسية لها تأثير كبير على عملية الحماية الكاثوديه للتأكد من أدائها.

يتم اختبار التيار المسلط، باستخدام ثلاث قيم للفولطية أقل من جهد الحماية المساوي لـ v (-0.85 ,-0.65 ,-) في وسط ملحي متغير التراكيز g (5, 10, 20, 35) من كلوريد الصوديوم ولمسافات مختلفة بين الكاثود والانود cm (2, 25, 50) ودرجات حرارة مختلفة °C (20, 30, 40).

أظهرت النتائج ان (E potential) تكون أكثر سلبية مع زيادة التركيز للملح ودرجة الحرارة وبعد المسافة الاقل كذلك تزداد كثافة تيار الحماية الكاثودية مع زيادة التركيز للملح وزيادة درجة الحرارة والمسافة بين الاقطاب. حيث عندها زاد معدل التآكل مع زيادة تركيز الملح ودرجة الحرارة .

جمهورية العراق

وزاره التعليم العالي والبحث العلمي

جامعة بابل كلية الهندسة

قسم الهندسة الكيمياوية

التحكم في التآكل عن طريق الحماية الكاثودية لخطوط أنابيب الصلب منخفضة الكربون في محلول الملح

الرسالة

مقدمة الى كلية الهندسة -جامعه بابل وهي جزء من متطلبات نيل الماجستير في الهندسة\ الهندسة الكيمياوية

من قبل

غفران عبد الكريم عباس

اشراف

ا.م.د. شاكر صالح بحر

2023