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Investigating The Implementation of the Impressed Current and Sacrificial Anode Cathodic Protection Methods for Carbon Steel at Different Environmental Conditions

A Thesis

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By

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Abstract

Metal structures buried in soil or water are exposed to great damage due to corrosion processes, which cause a serious engineering and economic problem all over the world.

This problem has received a wide range of international attention through the large amount of literature and research in this field. Also, many attempts have been made to overcome it through the use of different types of techniques. The most common and feasible technique is cathodic protection (CP).

CP has wide applications in various structures and is an effective electrochemical technique to mitigate or prevent corrosion of metal structures.

A specimen of carbon steel with a length of 100 mm, a width of 10 mm, and a thickness of 6 mm is used. A glass basin of dimensions (600 x 300 x 200) mm, the distance between the electrodes is fixed at 500 mm. The graphite electrode in the ICCPs system and the aluminum alloy in the sacrificial anode system (SACPs) are used as anodes. Several variables are studied that affect the cathodic protection of the metal including sodium chloride concentration (0.5, 1.5 and 3) g/L of distilled water, changing the pH of the solution (4, 7 and 10) and temperatures (20, 30 and 40) °C.

Four open circuit potentials of metal (-700, -900, -1000 and -1200) mV are used versus the Cu/CuSO₄ reference electrode.

The cathodic protection current density as well as the potential is measured for 2 hours. A comparison is made between ICCP and SACP. The results indicate that SACPs are better than ICCPs at -700, -900, and -1000 mV.

DEDICATION

I dedicate this thesis with love to those who have always been the ones to devote themselves to me, who have held my hand and supported me to complete my studies.

To

My husband Ghassan

I would like to express my deep thanks for standing by my side, helping me financially and morally, and encouraging me to finish my studies. You were the best support for me in this journey, may God protect you.

My Parants (mom and dad)

Who inspired me and gave me strength.

My children (Mohammed and Mujtaba)

They are my strength and the candles that shine in the dark.

Finally, I have no words to thank and express my deepest truth I owe to my family (brothers and sisters) for their constant efforts of encouragement during my studies

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Table of Contents

	<u>Page</u>	
<i>Abstract</i>		
<i>Dedication</i>	I	
<i>Acknowledgments</i>	II	
<i>Table of Contents</i>	III	
<i>List of Tables</i>	VII	
<i>List of Figures</i>	X	
<i>Nomenclature</i>	XIII	
<i>Abbreviations</i>	XVII	
CHAPTER ONE		
INTRODUCTION		
1.1	The Electrochemical Corrosion	1
1.2	Corrosion Protection Technology	3
1.3	Basic Theory of Cathodic Protection	3
1.4	Cathodic Protection Methods	6
1.4.1	Impressed current Cathodic Protection	6
1.4.2	Sacrificial (Galvanic) Anode Cathodic Protection System (SACPs)	7
1.5	The Aim of The Study	8
1.6	Thesis Organization	9

CHAPTER TWO

Theoretical Background And Previous and Recent Works

2.1	History of Cathodic Protection	10
2.2	Sacrificial Anode Cathodic Protection System (SACPs)	10
2.2.1	Advantages of Sacrificial Anodes	12
2.2.2	Disadvantages of Sacrificial Anodes	13
2.2.3	Applications	13
2.3	Impressed Current Cathodic Protection	13
2.3.1	DC Power Source	13
2.3.2	The Auxiliary Anode	14
2.3.3	The Reference Electrode	17
2.3.4	Advantages of The ICCP System	18
2.3.5	Disadvantages of ICCP System	19
2.3.6	Applications	19
2.4	The Electrical Criteria of the CP System Design	21
2.4.1	The Protection Potential	21
2.4.2	The Requirement of Current Density	26
2.5	Cathodic Protection Efficiency	28
2.6	Major Environment Factors Affecting the Cathodic Protection	31
2.7	Previous and Recent Works	33

CHAPTER THREE
Experimental Work

3.1	Experimental Work	46
3.1.1	Cathodic Protection Rig and Tests Devices	46
3.1.2	The Experimental Procedure	50
3.1.2.1	Preparing The Piece of Steel	50
3.1.2.2	Connections	50
3.1.2.3	Design of The Cathodic Protection System	51
3.1.2.4	CP System Measurements	54

CHAPTER FOUR
EXPERIMENTAL WORK

4.1	The Effect of Cathodic Protection Parameters	55
4.2	The Effect of PH on Protection Current Density	63
4.3	The Effect of Temperature on Protection Current Density	72
4.4	The Influence of Time on Protection Current Density	78
4.5	Comparison of Sacrificial Anode and Impressed Current Cathodic Protection Methods	82

CHAPTER FIVE
CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE
WORK

5.1	Conclusions	92
5.2	Recommendations	93
	<i>References</i>	94

List of Tables

<u>Table</u>	<u>Title</u>	<u>Page</u>
2.1	Galvanic anode characteristics	12
2.2	Impressed current anodes	15
2.3	Protective potential in seawater and soil for available types of reference electrodes at 25C°	18
2.4	Comparison of sacrificial anode and impressed current cathodic protection	20
2.5	Potentials required for protection	25
2.6	Cathodic protection criteria	26
2.7	Typical current density requirements to protect uncoated steel	27
2.8	Summary of experimental studies of the ICCPs method	40
2.9	Summary of experimental studies of the SACPs method	44
3.1	Chemical composition of carbon Steel plate	46
3.2	Chemical composition of aluminum alloy	47
4.1	Current density vs NaCl concentrations at different values pH, different applied voltages and a solution temperature of T= 20 °C.	58

4.2	Current density vs NaCl concentrations at different values pH, different applied voltages and a solution temperature of T= 30 °C.	58
4.3	Current density vs NaCl concentrations at different values pH, different applied voltages and a solution temperature of T= 40 °C.	59
4.4	Current density vs NaCl concentrations at different values of pH, and at different values temperature.	63
4.5	Current density vs pH values at different concentrations, different applied voltages and a solution temperature of T= 20 °C.	67
4.6	Current density vs pH values at different concentrations, different applied voltages and a solution temperature of T= 30 °C.	67
4.7	Current density vs pH values at different concentrations, different applied voltages and a solution temperature of T= 40 °C.	68
4.8	Current density vs pH values at different concentrations and a different temperature.	71
4.9	Current density vs Temperature at different pH, different applied voltages and 0.5 NaCl concentration.	74
4.10	Current density vs Temperature at different pH, different applied voltages and 1.5 NaCl concentration.	75
4.11	Current density vs Temperature at different pH, different applied voltages and 3 NaCl concentration.	75
4.12	Current density vs. Temperature at different pH and different NaCl concentrations.	78
4.13	Current density vs. Time at different concentrations, different pH values and T = 20 °C.	81

4.14	Current density vs. Time at different concentrations, different pH values and T = 30 °C.	81
4.15	Current density vs. Time at different concentrations, different pH values and T = 40 °C.	81
4.16	Comparison of ICCPs and SACPs in 0.5 NaCl concentration at different protection voltages, different pH value and a solution temperature T=20°C.	86
4.17	Comparison of ICCPs and SACPs in 0.5 NaCl concentration at different protection voltages, different pH value and a solution temperature T=30°C.	86
4.18	Comparison of ICCPs and SACPs in 0.5 NaCl concentration at different protection voltages, different pH value and a solution temperature T=40°C.	87
4.19	Comparison of ICCPs and SACPs in 1.5 NaCl concentration at different protection voltages, different pH value and a solution temperature T=20°C.	88
4.20	Comparison of ICCPs and SACPs in 1.5 NaCl concentration at different protection voltages, different pH value and a solution temperature T=30°C	88
4.21	Comparison of ICCPs and SACPs in 1.5 NaCl concentration at different protection voltages, different pH value and a solution temperature T=40°C.	89
4.22	Comparison of ICCPs and SACPs in 3 NaCl concentration at different protection voltages, different pH value and a solution temperature T=20°C.	90
4.23	Comparison of ICCPs and SACPs in 3 NaCl concentration at different protection voltages, different pH value and a solution temperature T=30°C.	90
4.24	Comparison of ICCPs and SACPs in 3 NaCl concentration at different protection voltages, different pH value and a solution temperature T=40°C.	91

List of Figures

<u>Figure</u>	<u>Title</u>	<u>Page</u>
1.1	Schematic showing a differential corrosion cell	2
1.2	Basic CP installation	4
1.3	Schematic illustration of partial cathodic protection of steel in an aerated environment	5
1.4	Polarization diagram illustrating principle of cathodic protection	6
1.5	Impressed current cathodic protection	7
1.6	Sacrificial (Galvanic) Anode Cathodic Protection system	8
2.1	structure to electrolyte potential measurement	22
2.2	Measurement of the potential of structures and the meaning of the measure	23
2.3	Effect of temperature on corrosion rate	32
3.1	The experiment units	49
3.2	Specimen (a) before cleaning (b) after cleaning	50
3.3	Photo of the Installed ICCP System	52
3.4	Schematic Diagram of The Installed ICCP system	53
3.5	Schematic Diagram of The Installed SACP system	53
4.1	Current density vs NaCl concentrations at different values of pH, an applied voltage of -700 mv and solution temperature of T= 20 °C.	56

4.2	Current density vs NaCl concentrations at different values of pH, an applied voltage of -700 mv and a solution temperature of T= 30 °C.	57
4.3	Current density vs NaCl concentrations at different values of pH, an applied voltage of -700 mv and a solution temperature of T= 40 °C .	57
4.4	Current density vs NaCl concentrations at different applied voltage, a solution pH =7 and temperature T= 20 °C.	60
4.5	Current density vs NaCl concentrations at different values of pH and a solution temperature of T= 20 °C.	61
4.6	Current density vs NaCl concentrations at different values of pH and a solution temperature of T= 30 °C.	62
4.7	Current density vs NaCl concentrations at different values of pH and a solution temperature of T= 40 °C.	62
4.8	Current density vs. pH values at different Nacl concentration -700 mv and T=20 °C.	65
4.9	Current density vs. pH values at different Nacl concentration -700 mv and T=30 °C.	65
4.10	Current density vs. pH values at different Nacl concentration -700 mv and T=40 °C.	65
4.11	Current density vs pH values at NaCl concentrations at different applied voltage, 0.5% NaCl concentration and temperature T= 20 °C	66
4.12	Current density vs. pH values at different Nacl concentration and T=20 °C.	70
4.13	Current density vs. pH values at different Nacl concentration and T=30 °C.	70
4.14	Current density vs. pH values at different Nacl concentration and T=40 °C.	71
4.15	Protective Current density vs. Temperature at different pH, 0.5 Nacl concentration and -700mv.	72

4.16	Protective Current density vs. Temperature a at different pH, 1.5 NaCl concentration and -700mv.	73
4.17	Protective Current density vs. Temperature at different pH, 3 NaCl concentration and -700mv.	73
4.18	Protective Current density vs. Temperature at different applied voltages, 0.5 NaCl concentration and pH =7.	76
4.19	Current density vs. Temperature at different pH and 0.5 NaCl concentration.	77
4.20	Current density vs. Temperature at different pH and 1.5 NaCl concentration.	77
4.21	Current density vs. Temperature at different pH and 3 NaCl concentration.	78
4.22	Current density vs. Time in 0.5 NaCl concentration at different pH values and T = 20°C.	80
4.23	Current density vs. Time in 0.5 NaCl concentration at different pH values and T = 30 °C.	80
4.24	Current density vs. Time in 0.5 NaCl concentration at different pH values and T = 40°C.	81
4.25	Comparison of ICCPs and SACPs in 0.5 NaCl concentration at different protection voltages, a solution temperature T=20°C and pH value of 7.	83
4.26	Comparison of ICCPs and SACPs in 0.5 NaCl concentration at different protection voltages, a solution temperature T=30°C and pH value of 7.	83
4.27	Comparison of ICCPs and SACPs in 0.5 NaCl concentration at different protection voltages, a solution temperature T=40°C and pH value of 7.	84

Nomenclature

<u>Symbol</u>	<u>Meaning</u>	<u>Unit</u>
μ	Seawater viscosity	N.s/m ²
A	Total structure surface area	cm ²
C	Nacl concentration	g/L
CE	Coating efficiency	
CO ₂	Concentration of oxygen	mg/L
CR	Corrosion rate	Mpy
D	Diffusivity	m ² /s
E	Activation energy	V
E _{corr}	Corrosion potential	V
F	Faraday constant (96500)	Coulomb/equiv
I	Current density	μ A/cm ²
i _{corr}	Corrosion current	μ A/cm ²
i _{cp}	Cathodic protection current density	μ A/cm ²
i _o	Exchange current density	μ A/cm ²
J	Mole flux	kg /m ² . s
K	The rate constant	Mol/L.s
K	Conductivity	mmho.cm ⁻¹
k _d	Mass transfer coefficient	m/s
R	Universal gas constant	J/K·mol
T	Temperature	K
Δ	Thickness of the diffusion layer	cm

Abbreviations

<u>Symbol</u>	<u>Meaning</u>
ANFIS	Adaptive Neural Inference
ASTM	American Society for Testing and Materials
AWWA	American Water Works Association
CP	Cathodic protection
CS	Carbon steel
HSCI	High Silicon Cast Iron
ICCP	Impressed Current Cathodic Protection
IR	Ohmic Drop
ISO	International Organization For Standardization
MMO	Mixed Metal Oxide -Coated Electrode
NACE	National Association of Corrosion Engineers
NaCl	Sodium chloride
PSP	The tube-Soil Potential
SACP	Sacrificial Anode Cathodic Protection

Chapter One

Introduction

Corrosion is the destruction of a metal under the influence of chemical or electrochemical factors of the surrounding environment. Entire countries pay a heavy price every year for maintenance, inspections, alterations of structures, machinery, corroded pipelines, and much more (**Huang, et.al. , 2018**). The global direct costs related to infrastructure corrosion - bridges, pipelines, etc. are estimated at more than \$ 1 trillion annually. The situation is expected to increase by a factor of 2-5 by 2050 (**Angst, U. M., 2019**).

In addition to the indirect costs that can exceed the cost of the direct costs. (**Pedefferri, P., 2018**). Therefore, it became necessary to search for techniques to reduce corrosion, the most common of which are cathodic protection, anti-corrosion injection, or the choice of a resistance material and design improvement.

1.1 The Electrochemical Corrosion

Corrosion is an automatic thermodynamic electrochemical process that involves removing electrons from the metal by means of anodic oxidation reactions. These electrons are consumed by cathode reduction reactions. This occurs due to the potential difference between the anode and cathode. The electrochemical cell, as shown in Figure (1.1), consists of:

- 1- **An anode:** the part where corrosion occurs (oxidation reaction), Where electricity is passed by chemical means from the surface of the metal into the electrolyte. This chemical reaction is an oxidation reaction

characterized by the metal losing an electron and combining with another element.

2- **A cathode:** The part in which the protection (reduction reaction) occurs, where electricity is transmitted by chemical means from the electrolyte to the surface of the metal.

3- **The electrolyte:** the part that allows the ions flow between the cathode and the anode. The electrolyte is the part of a corrosion cell which allows oxidation and reduction reactions to occur. The electrolyte includes the source of elements or atoms that are required for ion transfer to and from the metal electrodes (anode and cathode).

4- **The metallic path:** the part of the corrosion cell completes the circuit between the cathode and the anode and allows the electrons to move (Guyer, J. P. (Ed.), 2018). To understand how a cathodic protection system works, it is extremely important to understand these four parts of electrochemical corrosion.

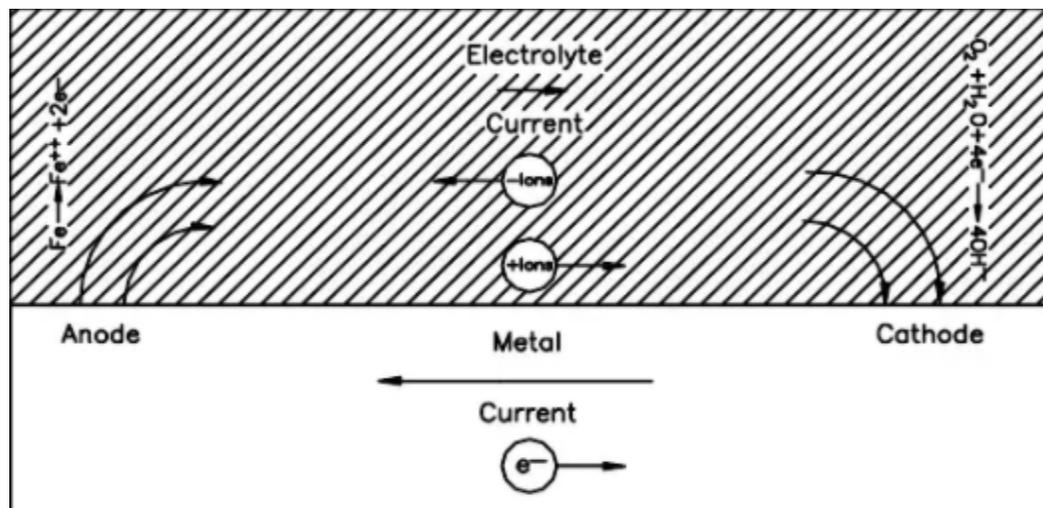


Figure (1.1): Schematic showing a differential corrosion cell (Peabody, A. W., 1971).

1.2 Corrosion Protection Technology

The methods of metal corrosion protection can be divided into the isolation control method (Metal coating, Nonmetallic coating, Chemical converting film coating), the thermodynamics control method (Cathodic protection, Anodic protection, Passivation treatment), and the kinetics control method (Corrosion resistant material selection, Corrosion inhibitor adoption, Corrosion environment change) (HUANG, Yongchang, et al., 2018).

1.3 Basic Theory of Cathodic Protection

Cathodic protection (CP) is an effective engineering method for reducing the corrosion rate. Protection is achieved by providing an external current to the metal to be protected, either by providing an external current source or using an anode electrode with a more negative voltage.

As the current source supplies the structure with negative electrons and supplies the positive electrode to the positive current, and then sends the positive current to the structure and then returns to the current source again (Revie, RW, 2008) as shown in Figure (1.2).

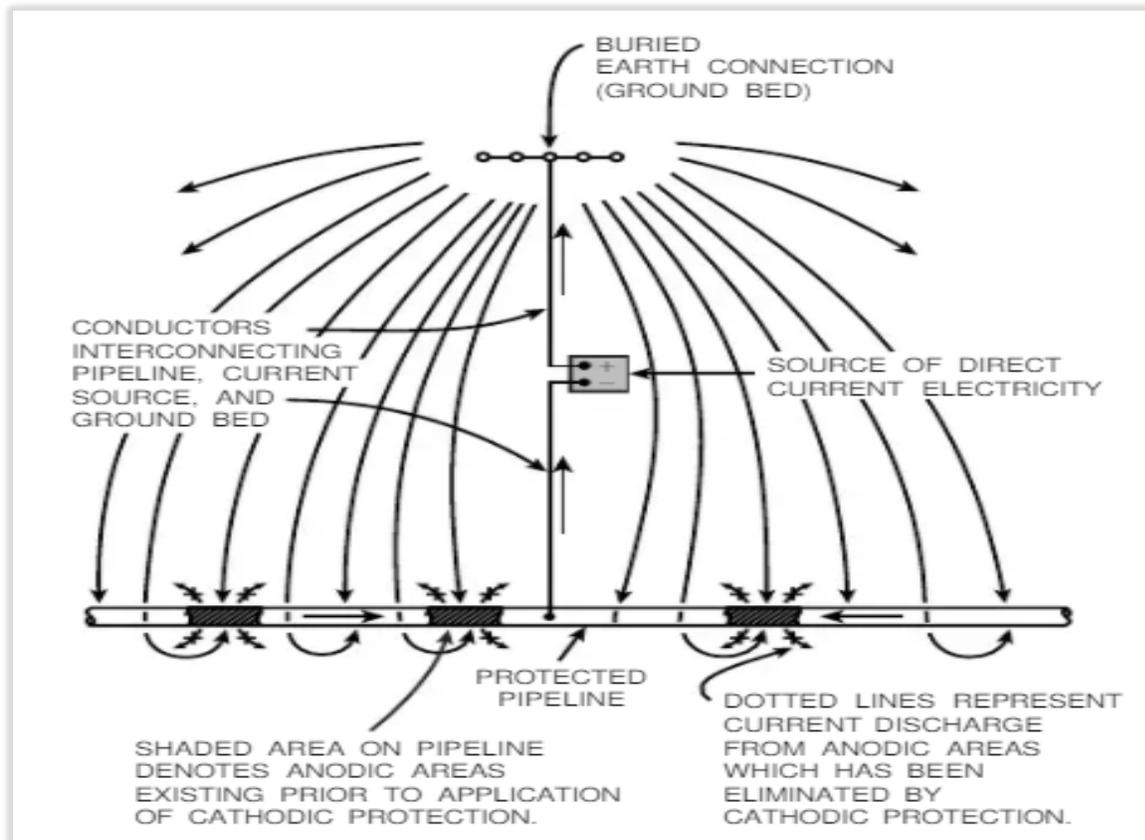


Figure (1.2): Basic CP installation (PEABODY, A. W., et al., 2001)

This technology has been applied in various industrial fields to protect metal structures and devices from corrosion, including, underground structures, exposed marine structures, ship hulls and heat exchangers. (Kakuba, G. ,2005).

The main reactions that occur when a metal comes into contact with a liquid surface, the variation occurs due to the difference in electrical charge at the solid-liquid interface, for example, iron dissolves in water in the form of positive ions (ferrous ions).



Without the presence of air or oxygen, the hydrogen ions can be reduced and devolving as a hydrogen molecule.



In the case of air, the most likely reaction is the oxygen reduction. There are two possible reactions.



The reduction of oxygen with the formation of water occurs in acidic media, as in its equation (1.3). On the other hand, the reduction of oxygen with the formation of hydroxyl ions occurs in the neutral or base environment (1.4). In both cases there is an increase in the alkalinity of the solution at the cathode as shown in Fig. (1.3), this is the basis of cathodic protection (**CHARNG, T., LANSING, F ,1982**).

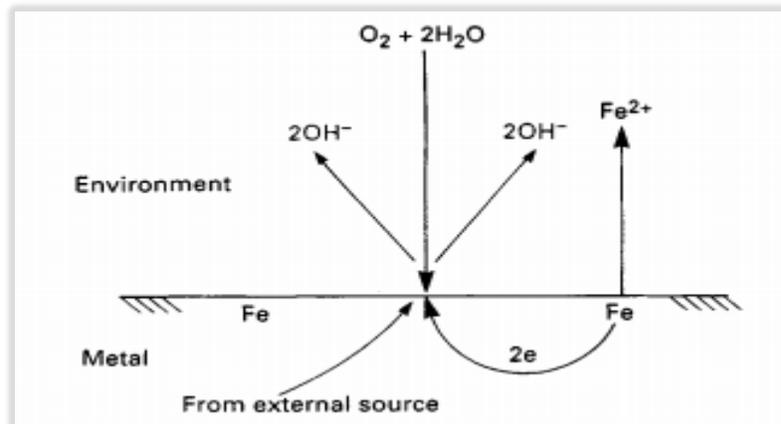


Figure (1.3): Schematic illustration of partial cathodic protection of steel in an aerated environment (**Shreir, L. L. (Ed.) ,2013**)

The principle of cathodic protection can be expressed through the polarization diagram as in Fig. (1.4). (Popov, et.al., 2018).

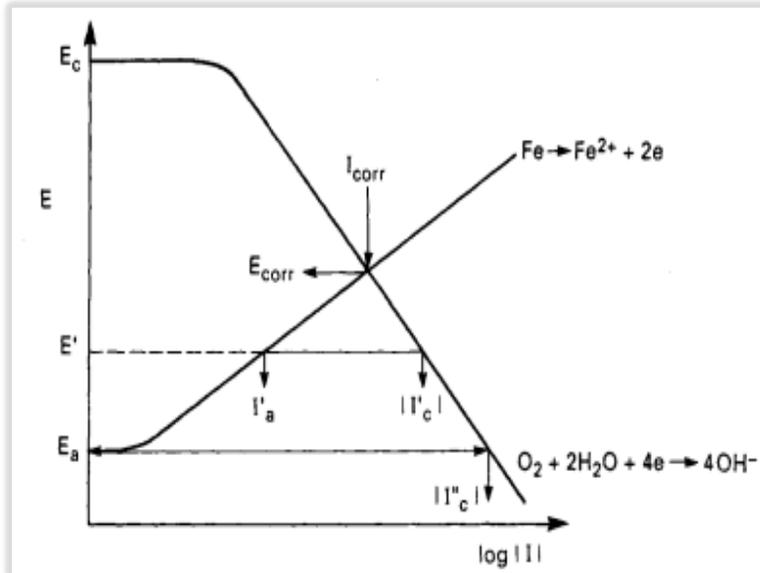


Figure (1.4): Polarization diagram illustrating principle of cathodic protection

(Ashworth, V. ,2010)

1.4 Cathodic Protection Methods

The cathodic protection consists in changing the voltage of the metal structure so that it is located in the immune zone.

1.4.1 Impressed Current Cathodic Protection

The ICCPs technology is widely used to protect buried pipelines and ship hulls submerged in seawater. The electrical circuit for this method uses an external current source, the negative terminal is connected to the metal that needs protection, and the positive terminal is connected to the auxiliary electrode immersed in the same medium to complete the electrical circuit.

The system consists 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. Figure (1.5) illustrates this method.

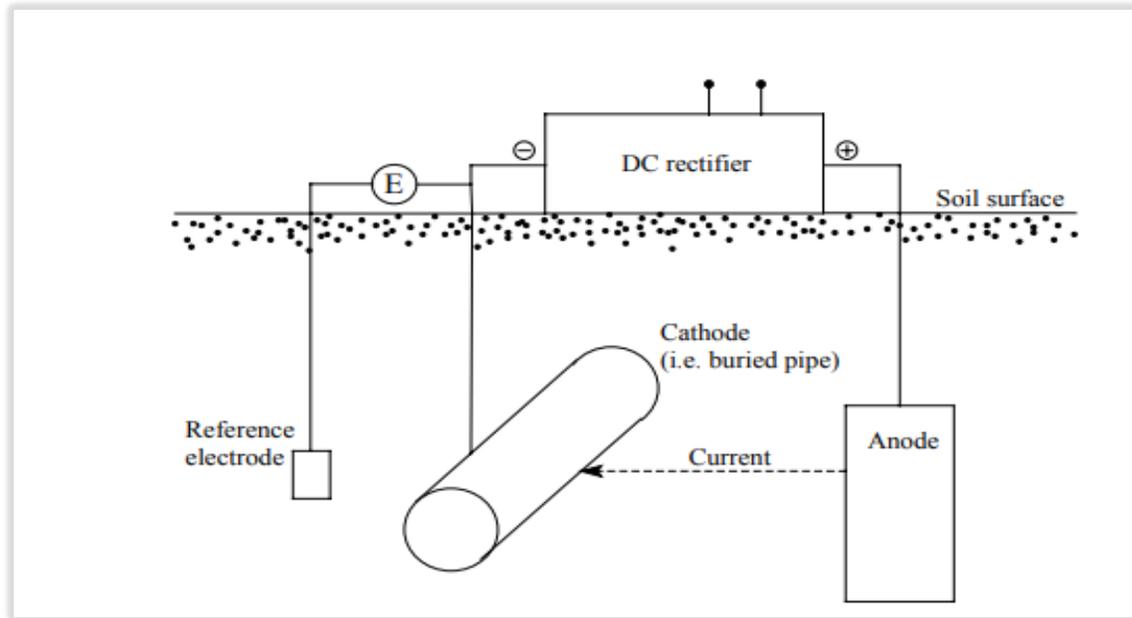


Figure (1.5): Impressed current cathodic protection (EL-Alem, et.al., 2013)

1.4.2 The Sacrificial (Galvanic) Anode Cathodic Protection System (SACPs)

SACPs consists of two electrodes of dissimilar metals that electrically connected to the electrolyte solution, where a current pass between them as a result of the difference in the electrochemical potential of the metals. The metal with the more electropositive potential (noble) becomes cathode and protected from corrosion, while the metal with more electronegative potential (active) becomes anode. As shown in fig. (1.6).

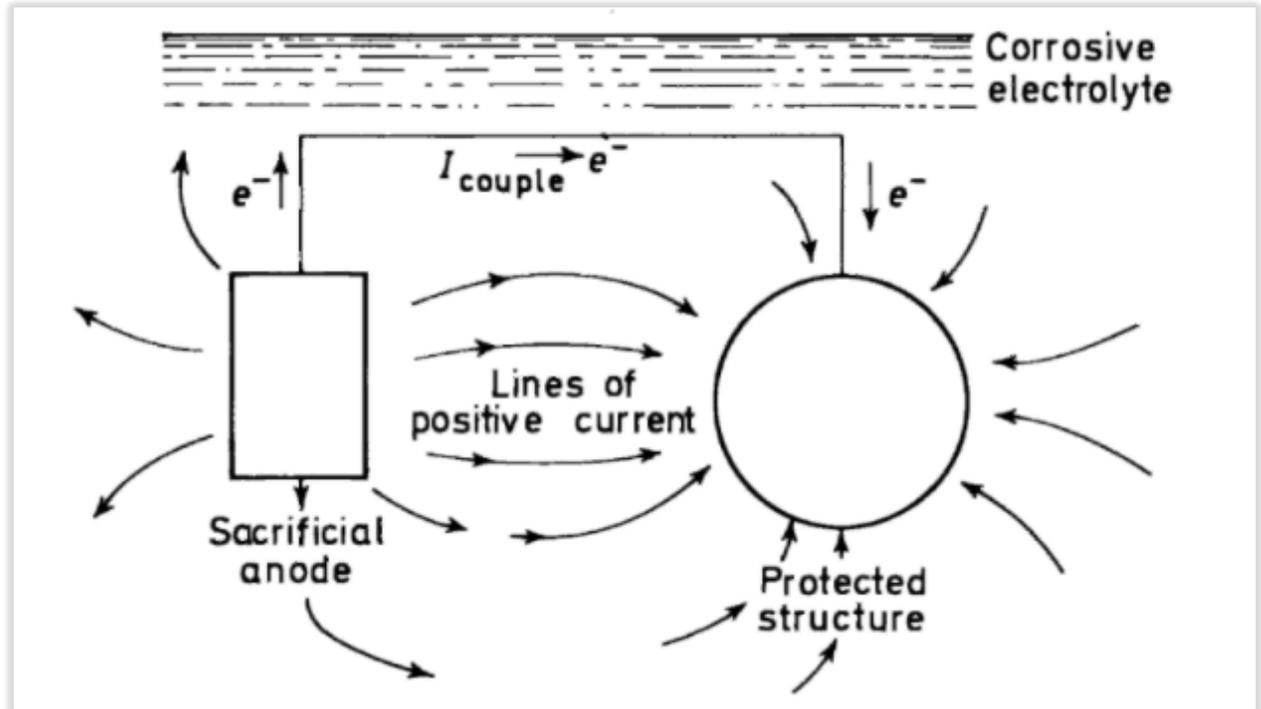


Figure (1.6): Sacrificial (Galvanic) Anode Cathodic Protection system (EL-Alem, et.al., 2013)

1.5 The Aim of The Study

The aim of the work is to study the factors affecting the cathodic protection of submerged and uncoated carbon steel structures. These factors include the electrolyte conductivity (salt concentration), pH, and temperature. Cathodic protection is used for the impressed current and sacrificial (galvanic) anode protection. The anodes are of graphite in ICCP and aluminum alloys by the method of SACP. The protection current was measured at each variable in the electrolyte solution and at every protection voltage used in this work (-700, -900, -1000, -1200) mv vs Cu\CuSo₄ reference electrode. Clarify the best result obtained and compare the two methods)Impressed current and sacrificial anode).

1.6 Thesis Organization

This thesis has been constructed into five chapters including the introduction in chapter one. The other chapters were structured as follows:

- **Chapter Two:** gives an overview of the background and history of cathodic protection. Methods of cathodic protection will be discussed in terms of the benefit, harm, application, and conditions of the anodes used for each method, in addition to previous studies on cathodic protection.
- **Chapter Three:** presents experimental work dealing with the installation of a CP system by Impressed current and sacrificial anode, and system operation.
- **Chapter Four:** Displays the data obtained during the work in the form of figures, analyzing and discussing the results.
- **Chapter Five:** gives conclusions, and suggestions for future work.

Chapter Two

Theoretical Background and Previous and Recent Works

Cathodic protection is an effective technique for buried and submerged structures to reduce corrosion by stopping the current flow from the metal to the electrolyte by neutralizing it with a stronger current from an external source (**Bashi, S. M., Mailah, N. F., & Radzi, M. M. ,2003**). Two methods of providing protection current are sacrificial anode and impressed current.

2.1 History of Cathodic Protection

The first scientific use of cathodic protection in 1820 was attributed to Mr. Humphrey Davy, as a result of scientific experiments in marine waters. By combining it with iron or zinc, copper could be successfully protected from corrosion, and the copper became cathodically protected.

All these experiences of Mr. Davey were helped by his disciple Michael Faraday, who continued his research after Davey's death. In 1834 Faraday discovered the quantitative relationship between corrosion-induced weight loss and electric current, thus laying the foundation for the future application of cathodic protection.

2.2 Sacrificial Anode Cathodic Protection system (SACPs)

In the first chapter, the principle of this technology is discussed, which uses the natural potential difference between the structure to be protected and the other metal in the same environment to provide driving effort. Therefore, the anode material is a very important part to provide the electrons needed for the cathodic polarization of the structure and it must include the following characteristics (**Popov, et.al.,2018**):

- 1- The potential of the anode should be negative enough to provide enough electrons for the metal equipment or structures to be protected and cathodically polarized. It should not be extremely negative to avoid the release of hydrogen gas in the cathode region, thus damaging the coating or bombarding the hydrogen. In general, the potential difference between the anode and the structure is often called the driving potential, about 0.25V.
- 2- The electrical capacitance of the anode material should be large, and its efficiency is high. The electricity generated by metal dissolution should be mostly for cathodic protection, the self-corrosive current of the anode is small. The current efficiencies of the sacrificial anodes range from (80-90) % except for the low current efficiency of the magnesium anode.
- 3- Low anode polarizability.

Table (2-1) shows the electrochemical properties of the alloys of the anode materials (**Revie, R. W.,2011**).

Table (2-1): Galvanic anode characteristics

Material	Theoretical Output (A-h/kg)	Actual Output (A-h/kg)	Eff.	Consumption	
				Rate (kg/A-year)	Potential to CSE
Zinc Type I (Cu, Al, Si, Fe, Pb, Cd)	860	781	90%	11	1.06
Zinc Type II (Cu, Fe, Hg)	816	739	90%	12	1.10
Magnesium H-1 alloy (Cu, Al, Si, Fe, Mn, Ni, Zn, ,others)	2.205	551 – 1.279	25 - 58%	6.8 - 16	1.40 – 1.60
Magnesium High Potential (Cu, Al or Si, (Fe), Mn, Ni, ,others)	2.205	992 – 1.191	45 – 54 %	7.3 – 8.6	1.70 – 1.80
Al/Zn/Hg	2.977	2,822	95%	3.1	1.06
Al/Zn/In	2.977	2.591	87%	3.3	1.11
Al/Mn/others	2.977	2640	88%	3.2	0.7-0.9

2.2.1 Advantages of Sacrificial Anodes

- 1- There is no need for an external electrical source, so there is no danger to divers
- 2- The installation of the system is relatively simple, i.e. eliminating the problems of incorrect installation. Additional anodes can be used to achieve adequate protection in the case of protecting a large metal installation.
- 3- Low installation and maintenance costs.
- 4- The overall current of each anode is limited; thus, the overload protection is low in risk and hydrogen embrittlement (Tiwari, et.al.,2014).

2.2.2 Disadvantages of Sacrificial Anodes

- 1- Periodic replacement is necessary for the anodes due to the limited output current (the life of the anode is limited).
- 2- The current cannot be changed or adjusted when environmental conditions change (contamination, paint damage, etc.).
- 3- It requires a large number of anodes to protect a large structure that increases the frictional drag and weight.
- 4- It is not economical to protect large and poorly coated pipelines **(Tiwari, et.al.,2014)**.

2.2.3 Applications

SACP systems are mainly used for applications where current requirements are small such as structures with limited surface area exposed to corrosive medium such as soil or water. Some of these applications could be small storage tanks, small boats, ballast tanks and initial installations of offshore structures.

2.3 Impressed Current Cathodic Protection

This system is widely used for pipelines, ships, offshore production platforms, wastewater treatment equipment, and more. The main advantage is its output capacity is much greater than the sacrificial anode method. Therefore, this method is best suited to protect large, poorly painted, and unpainted structures.

(Bushman, J. B. ,2010). 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.

2.3.1 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 (Ahmad, Z. ,2006) .

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 (Huang,et.al. ,2018).

2.3.2 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.

(Popov, et.al, ,2005). The specification of the anode impressed current is provided in Table (2-2).

Table (2-2): Specifications of some impressed current anodes (Huang,el.at, ,2018).

Anode Material	Recommended Current density A/m ²	Maximum Voltage, V	Consumption Rate, g/A-yr	Comments
Scrap Steel	Varies	-	200 - 9,000	Difficult life prediction
Graphite	10	-	30 - 450	Very brittle
Silicon-Chromium-Cast Iron	10 - 100	-	90 - 250	Very brittle
Lead-Silver	250 - 500	-	30 - 90	Heavy, Poor mechanical properties
Lead-Platinum	100	-	2 - 60	
Magnetite	10 - 500	-	40	Very Brittle
Platinized Titanium	250 - 700	9	0.01	5 μm thick Pt film provides 10 year life
Platinized Tantalum	500 - 1000	100	0.01	5 μm thick Pt film provides 10 year life
Platinized Columbium	500 - 1000	100	0.01	5 μm thick Pt film provides 10 year life
Lithium-Ferrite Ceramic	15 - 2000	9.7	1-2	Lightweight and tough

Auxiliary anodes are divided into two classes: soluble anodes like scrap iron. An insoluble anode such as high-silicon cast iron, graphite, mixed metal oxide -

coated electrode (MMO), lead-silver alloy, platinum and platinum-plated electrode, and Lead alloy anodes.

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 $10.75\text{A}/\text{cm}^2$ in soil and $0.23\text{A}/\text{cm}^2$ in water. The graphite is designed in the soil with a maximum density of 930 cm^2 ampere, 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. (Von Baeckmann, et.al., 1997).

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 (Cicek, V. ,2013).

MMO-coated electrode has a very low dissolution rate that may reach ($5\text{ mg} / \text{A} \cdot \text{a}$). 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 (Huang, et.al. ,2018) .

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

consumption rate. Pure platinum is so expensive that it is used as a coating. It is usually used to coat noble base metals such as titanium and niobium, where the thickness of the coating generally ranges from 2.5 to 5 micrometers. The platinum coated titanium anode is restricted to low resistance environments such as sea water because the negative film of the anode begins to break down at 10 volts. Platinum coated niobium anode is used in power stations, inner tubes and tanks, and is used for high resistance electrolytes (**Pedefferri, P et.al.,2018**).

Steel and iron scrap: a consumable anode material that was used in the early years of cathodic protection system installations. The advantage of being available and cheap. This anode has a special application because the predominant anode reaction is the dissolution of iron, and gas production is restricted. The rate of consumption of mild steel scrap is 6.6 - 9 kg per ampere per year, for cast iron its rate of consumption is 0.9 - 9 kg per ampere per year, while the rate of consumption of steel scrap is generally uniform (**Ahmad, Z. ,2006**) .

Lead alloy anodes: These anodes are only used in marine applications and may use different metals such as antimony, tin and 1 to 2% of silver. One of the advantages of this anode is a black negative film of lead peroxide around the anode material, which leads to prolonging the life of the anode, as it results in a consumption of 0.09 kg per ampere per year, i.e., a low consumption rate. Under conditions of low chloride, the negative film does not form around the anode material and thus the anode is consumed rapidly (**Von Baeckmann, et.al. ,1997**)

2.3.3 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 cathodically protected by placing it as close as possible to the protected

structure to avoid the error caused by the IR drop in the electrolyte. Table (2-3) shows the different types of reference electrodes (AL-Shareefi, H. ,2009).

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.

Table (2-3): Protective potential in seawater and soil for available types of reference electrodes at 25C°.

Reference Electrode	Electrolyte	Protective Potential in 20Ω.cm seawater at 25C°
Saturated KCl	Seawater	-800 mV
Ag/AgCl	Seawater	-800 mV
Cu/CuSO ₄	soil	-850 mV
Zinc	Seawater	+240 mV

2.3.4 Advantages of The ICCP System

- 1- Flexibility to control the output current and voltage widely.
- 2- Applicable and effective in almost any resistant environment.
- 3- The ability to protect large metal structures and poorly painted pipelines.
- 4- Anode consumption is comparable to less sacrificial anodes.

- 5- High-current output requirement to protect the underground structures, thus a high cost (Tiwari, et.al. ,2014).

2.3.5 Disadvantages of ICCP System

- 1- The system needs to be monitored frequently. It may require repair once every several years.
- 2- Maintenance and operation costs are high.
- 3- These systems are exposed to the risk of over protection. If this happens, then it leads to paint stripping and hydrogen embrittlement.
- 4- ICCP systems are more complex and less powerful than galvanic systems in certain applications such as pipeline protection.
- 5- The problem of interference in other neighboring structures occurs in this system, it can be reduced by placing the devices near the protected structure.

2.3.6 Applications

Impressed cathodic protection systems are used for large scale systems or large structures, or for systems where the coating system is ineffective, or when the frame to be protected cannot be isolated from other exposed tubes. All of these systems need higher current requirements than those needed in SACP. Examples of these applications for forced current systems are (Heidersbach, R. ,2018):

- a. Bare piping systems (oil, gas, steam distribution).
- b. Copper concentric neutrals of electric distribution cables-fueling systems.
- c. large fuel storage tank.
- d. Large above grade storage tank bottoms.
- e. Water storage tank interiors.

- f. Wastewater process equipment.
- g. Shore-side structures such as piers, docks, bulkheads.

Table (2.4) shows the comparison between the two methods according to definition, principle and applications.

Table (2-4): Comparison of sacrificial anode and impressed current cathodic protection.

	Sacrificial anode system	Impressed current cathodic protection
DEFINITION	Sacrificial anode is a highly active metal that can protect the less active metal surfaces from corrosion.	Impressed current is a type of cathodic protection utilizing electrochemical means to obtain protection against corrosion
PRINCIPLE	Provide the protection by being more electronegative or much more anodic than the protected metal.	Provide the protection by converting the corroding the metal from anode to cathode.
METHOD	Metal or alloy is placed in order to act as the anode instead of the metal to be protected.	A DC current is provided to the metal to be protected in order to make it the cathode.
APPLIED MATERIAL	A metal or an alloy that an act as the anode.	A DC current supply.
APPLICATION	the protection of hulls of ships, water heaters, pipelines, underground tanks, refineries, etc.	protection of steel in seawater or soil, subsea pipelines, hull, oil platform in steel and concrete, concrete bridges placed in seawater, pipelines buried in soil, underground tanks, etc.

2.4 The Electrical Criteria of the CP System Design

Different terminals are available to determine whether the structure to be protected is adequately protected during the application of cathodic protection. The cathodic protection technique is mainly an electrochemical process, and electrochemical methods are widely used to determine the degree of protection of the structure. In addition to electrochemical methods, inspection processes to determine actual structural conditions can be used to determine if effective protection has been achieved.

For buried or submerged systems, access is restricted, as electrochemical methods are widely applied (**J.Paul Guyer ,2017**). Two primary electrical criteria for CP of buried or submerged structures. The first criterion is the protection potential (the structure-to electrolyte potential), and the second is the net protective current criterion.

2.4.1 The Protection Potential

This criteria indicating the degree of protection, including over protection, is widely accepted, and used by corrosion engineers. Based on this standard, a positive electrode is placed in contact with the environment (soil or water) connected to the negative electrode of the high resistance voltmeter. While the structure is connected to the positive pole of the scale, as shown in fig (2-1).

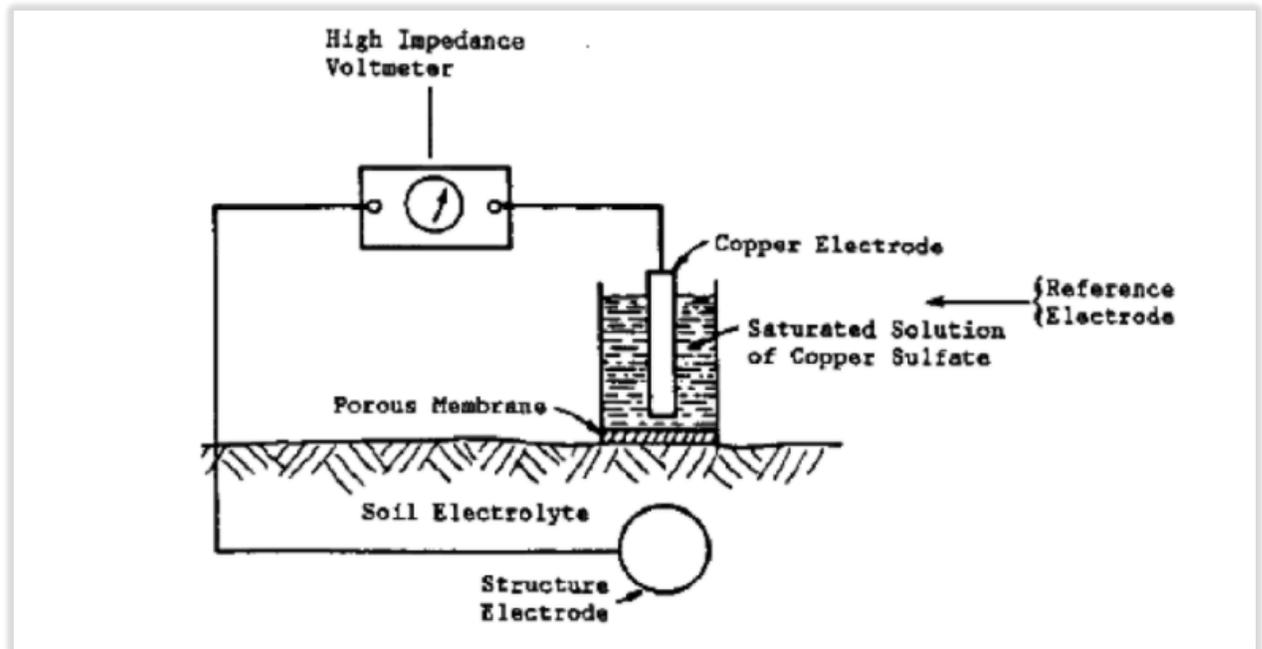


Figure (2-1): Structure to electrolyte potential measurement (Uhlig, H. H., et.al. ,1985).

The value of the potential measured with a voltmeter is called the structure-electrolyte potential (Uhlig, et.al. ,1985). The potentials to stop or reduce corrosion lie roughly in the range of -850 mv as opposed to a saturated copper / copper sulfate reference electrode according to RJ Kuhn's hypothesis for the first time in 1933. After extensive studies of cathodic protection, six criteria for complete protection of iron in soil or water accepted by the National Association of Corrosion Engineers (Popov, et.al. ,2005).

NACE RP-01-69 is the recommended practice for controlling external corrosion in buried or submerged tube systems specifying the following “A negative (cathodic) potential of at least -850 mV versus Cu / CuSO₄ should be applied to protect the structure”. As for the presence of sulfate bacteria, high temperatures, acidic environments, and dissimilar minerals, this standard is not

sufficient for protection, but the minimum protection level is -950mV (Ashworth, V. ,2010). under these conditions ,the anodic oxidation reactions on the iron surface will stop completely and the metal will not rust. The potential values for protecting different materials are shown in Table (2-5) and some other criteria are summarized in Table (2-6).

The IR drop at the structure / electrolyte interface must be considered according to NACE, which is included in most practical measurements, it is of uncertain value, depending on the position of the reference electrode with respect to the structure, the electrolyte resistance and the flowing current density. The IR drop is caused by the current flow through the electrolyte and the structure.

The presence of this drop changes the potential reading of the voltage measured by the reference electrode as shown in the fig (2-2).

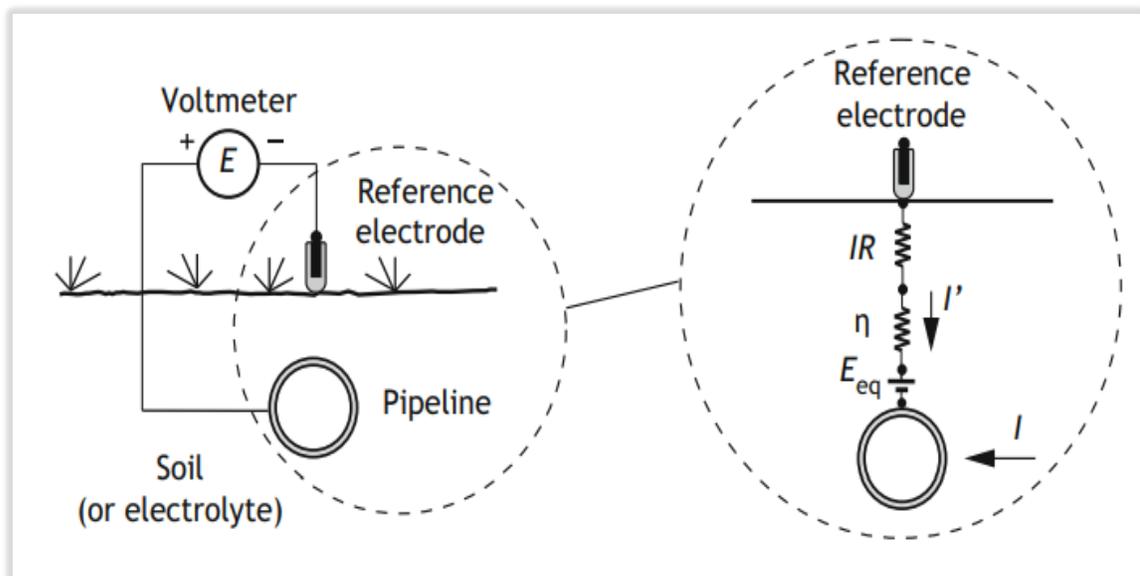


Figure (2-2): Measurement of the potential of structures and the meaning of the measure (Pedefferri, P., et.al. ,2018)

So, it must be eliminated to properly obtain the measured potential of the structure. There are two ways to eliminate it

- * Reducing the distance between the structure to be protected and the reference electrode.
- * Eliminate the circulating current.

In the first case, the reference electrode is placed as close to the frame as possible to reduce the electrolyte resistance. For buried structures, it is necessary to use fixed reference electrodes buried close to the structure with a maximum of 0.2 m.

In the second case it is eliminated by a method. When the protection current is interrupted, IR disappears in a very short time within 6-10 seconds. But this method is not valid in the presence of currents different from the protection current, such as stray currents. In addition to current interruption technique is very difficult to conduct for large structures such as pipelines (**Pedefferri, P., et.al. ,2018**).

To accurately determine the potential of a cathodically protected structure, there are three possible criteria (**Schmid F. J.,1999**):

1- Full Protection

The CP system can be offered with a full protection case with -850mV potential. It is measured with respect to the Cu/CuSO₄ reference electrode connected to the electrolyte.

2- Under Protection

Some corrosion in the structure occurs when the measured potentials of the structure are not negative as required by one or more of the standards applied for cathodic protection. However, body wear will be reduced by supplying it with external current.

When only the body parts do not reach the desired standards, those areas will erode at a rate inversely proportional to the current they receive. In this case, partial protection will occur. This means the wear is reduced in those areas that receive partial protection but not completely stopped. When the protective currents are completely interrupted, the corrosion usually returns to normal after a short period of time.

3- Over Protection

When the voltage applied to the frame exceeds the applied voltage, this condition occurs and the removal of the protective coating causes the generation of hydrogen gas, it is often trapped between the jacket and the surface and causes the appearance of blisters and the peeling of the coating, in addition to wasting the anode material or electrical energy as more external source will be needed.

Table (2-5): Potentials required for protection (Jones, L. ,1996).

Metal	Potential vs cu\cuso₄
Steel	-850 mv
Steel (sulfate reducing bacteria)	-950 mv
Copper alloy	(-500 to -650) mv
Lead	-600 mv
Aluminum	(-950 to -1200) mv

Table (2-6): Cathodic protection criteria (**Bushman, J. B. ,2010**).

Criterion	Measurement Condition	Comments
1. Potential less than -0.85 V versus Cu-saturated CuO_4 for steel	Current on (IR_{Ω} present)	Meaningful in some environments Uncertain due to IR_{Ω}
2. Cathodic polarization more than 300 mV active to corrosion potential of structure	Current on (IR_{Ω} present)	Uncertain due to interferences from IR_{Ω}
3. Cathodic polarization more than 100 mV active to corrosion potential of structure	Current interrupted (IR_{Ω} absent)	Interruption techniques difficult to implement
4. Cathodic polarization to a potential where Tafel behavior achieved	Current variable (IR_{Ω} present)	Difficult to determine in presence of IR_{Ω}
5. Net protective current flows from electrolyte into the structure surface	Unspecified	Correct in theory Difficult to determine in practice

2.4.2 The Requirement of Current Density

The protection current makes the electrolyte frame potentials equal to -850 mV. This represents the second criterion in the design calculations for cathodic protection systems.

The current required for cathodic protection depends on the metal being protected and on the environment. To achieve the protective potential required to accomplish the protection, current must flow from the anode to the protected structure. The amount of current required to protect a specific structure is proportional to the area of the structure exposed to the electrolyte. Therefore, current requirements are usually given current densities in amperes or milli-amperes (0.001 amps) per square meter (feet) of exposed surface (**Schmid F. J.,1999**).

The conditions of the structure surface determine the amount of current density required to change the capabilities of the structure to the required parameters, for example, the protection current required to protect the exposed

structure from corrosion is more than the protection current for the coated structure except for the defects of the coating.

The level of protection of the structure or the amount of current required is also affected by the environmental conditions of the buried or submerged structures, such as temperature, pH, ventilation flow rate, and conductivity. In the event of any change in the environment (soil or water), the output current of the anodes reaching the structure will be affected, the resistance of the electrolyte increases (the conductivity decreases), the output current decreases and vice versa. Table (2-5) indicates the estimate of current density in (mA/ m²) required to complete CP (Popov, et.at., 2005).

Table (2-7): Typical current density requirements to protect uncoated steel (Cicek, V. , 2013).

Environment	Current density (mA/m ²)
Neutral soil	4.30 to 16.14
Neutral soil well aerated	21.52 to 32.3
Wet-soil	26.9 to 64.58
Highly acidic soil	53.8 to 161.45
sulfate-reducing bacteria	Up to 452.08
Heated-soil	53.8 to 269.09
Stationary-freshwater	53.8
Moving-freshwater containing dissolved oxygen	53.8 to 161.45
Seawater	53.8 to 269.09

2.5 Cathodic Protection Efficiency

The efficiency criteria that we need to consider for a cathodic protection installation is the corrosion potential of the steel with respect to the reference electrode. The measurement of this important value in cathodic protection depends on the type of structure and its surrounding environment.

Attention should be paid to the value of the ohmic drop (coming from the current caused by electrical resistance) that exists between the measuring electrode and the surface whose potential we wish to measure can lead to large measurement errors. It is therefore necessary to eliminate or reduce this ohmic drop as much as possible either by placing the measuring electrode in the immediate vicinity of the metal surface, or more often by measuring the voltage immediately after which the cathodic protection current is cut off in the absence of external electrical disturbances.

And to confirm the effectiveness of the protection by the real potential value of the steel if it is less than -850 mV with respect to the copper electrode / saturated copper sulfate or -800 mV with respect to silver / silver chloride / sea water electrode, this is an acceptable value for protection. There are other empirical parameters, the most famous of which is the so-called “depolarization”: the potential of the steel is measured as quickly as possible after the cathodic protection current is turned off (therefore, we avoid the ohmic drop), and then a few hours later. Protection is considered effective if the corrosion potential of the protected structure is at least 100 mV higher.

Also, to determine the efficiency of the cathodic process is to determine the type of system required to obtain the highest possible efficiency, and this is determined by the method of the required current density and soil resistance. If the soil resistance

is low (<5000 ohm-cm) and the current density requirement is low (<1 mA per square foot), a galvanic system can be used. However, if the soil resistance and/or current density requirements exceed the above values, a forced current system should be used.

The value of the current required for protection must be monitored because any change in it means that there is a defect in the system, such as the moisture in the soil decreases, and the current decreases.

The protective current requirement for the required DC protective current (important part of design calculations for cathodic protection the systems in existing structures are the amount of current required per square foot (called current density) to change the potential of the structure to -0.85 V) is for any CP system depends on the physical dimension of the structure to be protected, rated current density, recess ratio (lack of coating or breakdown of coating), ambient temperature and site-measured soil resistance (All this must be specified before designing any system) . The required current can be calculated simply using

$$I = (A)(I') (1.0 - CE)$$

where I is total protective current, A is total structure surface area, I' is required current density, and CE is coating efficiency.

Choose the type of anode according to the system environment. All specifications of the anode must be taken into account in terms of dimension, weight, and the anode's driving potential, and from the current requirements of the system, the number of anodes required for protection will be determined. Knowing the number of anodes required is necessary to know the life of the system (Cicek, V. ,2013).

Choose the anode type according to the system environment. All anode specifications must be taken into account in terms of dimensions, weight and anode driving potential, and from the current requirements of the system, the number of anodes required for protection will be determined. It is necessary to know the number of anodes required to know the life of the system (Cicek, V., 2013). The most important part in choosing the anode is the efficiency of the anode (the percentage of the weight of the anode that has been sacrificed for CP purposes divided by the total theoretical ampere-hours or the capacity of the material used) and that the efficiency of the anode in the sacrifice system is not 100% because of self-corrosion.

The sacrificial anode must possess a large number of electrons per unit mass and must deliver these electric charges efficiently. Thus, the electrical output of the anode is given by the current capacitance which is expressed in Ah kg⁻¹ or kg A⁻¹ y⁻¹. The value of the current capacitance is determined by the electrochemical equivalent, density, and efficiency of the anodic material. The electrochemical equivalent, which depends on the atomic weight and valency, is one of the properties of the anode material.

The actual anode efficiency is determined by a number of factors including the nature of the environment, operating current density, and metallic microstructure. It is clear that if the reaction rate of the cathode on the anode is low, the efficiency will be high, so that there is minimal self-corrosion (Guyer, J. P. (Ed.), 2018).

2.6 Major Environment Factors Affecting the Cathodic Protection System

1- Conductivity:

Conductivity is a measure of solutions composition, which plays a vital role in corrosion in aqueous solutions and CP efficiency. The higher the conductivity, the greater the transport of ions and electrons. Like distilled water, it has a low conductivity due to the removal of dissolved species. Sea water is a solution full of ionic species and therefore its conductivity is very high (**Gjerde, O. , 2014**). Nacl is an ionic compound, thus when it is dissolved in water conducts electricity and cause further current flow which leads to more CP current required to achieve desired potential shift between cathode (pipe) and solution (**Merzah, et.al. ,2017**).

2- Temperature:

The rate of corrosion increases with increasing temperature due to the acceleration of oxygen diffusion towards the cathode of the oxygen reduction reaction. Temperature has an effect on the solubility of oxygen, as oxygen is one of the variables that has the greatest influence on the rate of corrosion, as the temperature increases, the level of oxygen participation in the corrosion rate decreases. for example, in a closed system, oxygen cannot escape. The rate of corrosion increases with the temperature until all the oxygen is consumed. And the open system, so oxygen is free and released to the atmosphere and the rate of corrosion increases with increasing temperature, until it reaches 80 degrees Celsius, which leads to a decrease in the solubility of oxygen at this temperature, as shown in the fig (2-3). (**Charng, et.al. ,1982**).

The temperature affects the corrosion potential, the cathodic protection current, and the CP efficiency, when the temperature is above 25 ° C, the -850

mv vs CSE standard cannot adequately protect the carbon steel. This means, as the temperature increases, the corrosion potential becomes more negative and the need for cathodic protection current increases (Kim, et.al., 2001).

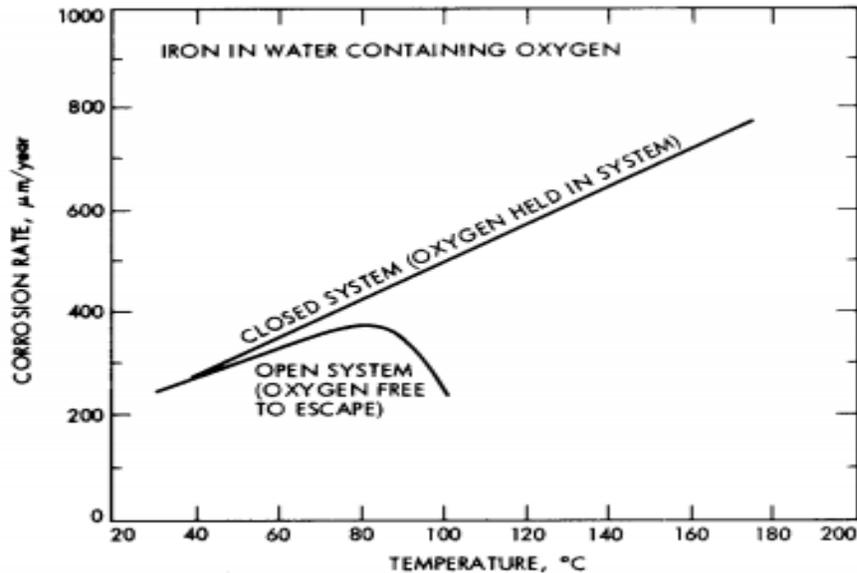


Figure (2-3): Effect of temperature on corrosion rate

3- pH electrolyte:

It represents a measure of the concentration of hydrogen ions in an electrolyte. It affects the corrosion rate by speeding up or slowing down chemical reactions at the surface of the anode or cathode. A pH value of less than 4 speeds up the corrosion rate. When CP is applied, the pH value gradually increases due to the cathodic reaction that leads to the generation of the hydroxyl ion and thus increases the alkalinity of the solution around the surface of the structure, which results in some significant side effects. The high pH environment will alter the corrosion behavior and performance of the CP system due to the formation of negative film which reduces the need for CP currents (Talbot et.al., 1998).

2.7 Previous and Recent Works

There are previous studies on the methods of applying cathodic protection and the effects of environmental characteristics on the potential distribution and current required for effective protection of the structure. Several experimental studies of cathodic protection can be summarized as follows:

Tao, D., et.al., (2005) studied cathodic protection by the ICCP method to reduce the rate of corrosion of mills used to grind acid phosphate slurries at acidity (2-4) in fertilizer plants in Florida. The effect of polarization voltage on corrosion rate and required current density was studied using a specially designed ball mill whose electrochemical potential can be controlled. The experimental results indicated that the overall corrosion rate decreased when applying the cathodic protection at a potential of 1 volt at a rate of (42-46) %, and the current density required to effectively reduce the corrosion was 210 mA /m² in a pH of 3.1 solution. 180 mA /m² in a pH 6.8 solution. 160 mA /m² in a pH 9.2 solution.

Hameed, et.al., (2007) Studies of cathodic protection by sacrificial anode system using zinc anode .They were placed in a container containing sea water (4% (weight / volume) NaCl), the solution conditions were changed in terms of temperature (0-45) degrees Celsius, flow rate (5-900) liters / hour, and pH value (2-12) with the duration of time (1-4) hours to examine the rate of zinc consumption with all these variables. It was found that the consumption rate measured by weight loss technique increases with an increase in temperature, flow rate and time, while it decreases with increasing the pH. The consumption of zinc in the first hour is greater than in the second hour.

Ajeel, et.al., (2008) designed a cathodic protection system for direct current to prevent corrosion of the low carbon steel tube (ASTM A179-84a) type as X60 with an outer diameter of 3 cm and a inside diameter of 2 cm. This system was used to study the effect of different conditions on the minimum cathode protection current. The studied variable conditions were the concentration of (0.01-3.5) % sodium chloride, the temperature of (30-50) degrees Celsius, the distance between the anode and the cathode of (10-20) cm and the pH solution (5-9). Electrochemical experimental results showed that the protection current density increases with increasing concentration, temperature, and pH, and increases slightly with increasing the distance between the anode and cathode. The effective sequence of these parameters of the current density is as follows:

Temperature > concentration > pH solution > cathode – anode distance.

Rashid, K. T. (2009) studied the effect of temperature, different NaCl concentrations and mixing velocity on the values of the cathodic protection current by sacrificial anode method was studied, using magnesium anode to provide protection for a sample of an iron steel tube with an outer diameter of 2.5 cm and a length of 8 cm. The sample is immersed in a basin in which a solution of Nacl concentration is 3.5% at temperatures (25, 35, 45, 55, 65) ° C and the speed of mixing the different solutions has been shown to increase the temperature causing an increase in the electrical conductivity of the solution and thus allows more current to pass through the electrolyte than magnesium anode to the structure. Also, the mixing speed leads to an increase in the cathodic protection current if its effect is clearer or higher than the temperature and conductivity.

Abud Al-Rahman, H. M. (2009) investigated the effect of both the environmental resistance and the anode-cathode distance on the protection current density of the

bare carbon coated steel tube of the ICCP system using graphite anode with a diameter of 1.3 cm and a length of 30 cm, a working electrode of 10 cm length, an inner diameter of 2 cm and an outer diameter of 2.5 cm. Noted an increase in the intensity of the protection current as the environment resistance decreases (the conductivity increases) and the distance between the electrodes increases. The CP current density of the coated tube is very low compared to the bare tube current density. The CP current density of the coated tube increased with decreasing resistance and increasing the coating defects.

Shamsuri, Siti Rahmah. (2010) determined the effect of soil properties and contents on the corrosive behavior of low carbon steel. The samples used are coated (with bitumen) low carbon steel and uncoated. Soil and water samples taken along pipelines in Bekok, 50 km in Yongping, showing soil properties: pH (1.76-5.6), temperature (25-50) °C , moisture content (20-40) % and resistance less than 1000 ohms.cm . These factors determine soil corrosion. Soil resistance decreases with increasing water content and ionic concentrations, according to the AWWA. The corrosion rate of the sample in the soil was examined using the Tafel slope, and the result was found that the corrosion rate increases significantly at a lower pH level (1 to 2) and the corrosion current density increases with the temperature. It was found that the uncoated sample has a greater corrosion rate than the plated sample.

Jabur S., A. (2014) demonstrated the effect of the environmental resistance (conductivity) and the distance between the anode and the cathode on the density of the cathodic protection current required to provide complete cathodic protection with the ICCP system for bare and coated tubes. A model of carbon steel tubes with epoxy sealing of tube ends, 10 cm long and submerged with a solution of distilled water and five different concentrations of NaCl was used to perform the protection test at

30 ° C. It was found that the density of the protection current increased with the decrease in the environmental resistance (the increase in conductivity) and the increase in the distance between the anode and the cathode of the bare tubes. As for the pipes coated by two different polymers, the protection current increased as the soil resistance decreases, and the number of defects increases.

Ali, A. (2014) studied the downstream cathodic protection system of a 100 cm long carbon steel tube buried in a wooden case immersed in soil. The effect of factors on protecting the pipe from corrosion, such as anode location (distance and depth), soil resistance (wet and dry), tube conditioning (coated and non-coated), the distribution of potentials and currents along the tube (cathode) and the amount of current required were investigated to achieve cathodic protection.

AS, A., KC, A., & JJ, A. (2015) investigated the attenuating effect of the cathodic protection system using the current applied technique on the corrosion of the buried steel pipeline. A sample of steel was buried for 60 days in a moderately corrosive and non-aggressive soil with a depth of 1 meter and soil pH= 6.97 with resistance 7850 ohm.cm. Uniform corrosion and galvanic corrosion were observed on the sample with a corrosion rate of 4.649 mph compared to the corrosion rate of the cathodically protected sample of 0.379 mph for the obtained efficiency of 92%, making cathodic protection an effective measure for controlling corrosion.

Zedin, et.al. ,(2015). Explained the sacrificial anode cathodic protection system (SACPs) for low carbon steel tank protection, using of carcass anodes and the effectiveness of the coating (with plating and electro-chemical deposition coating). Experimental tests were carried out on a covered tank (with electrochemical deposition coating) and a low carbon steel tank with and without a soluble anode (magnesium anode) by immersion in a 3.5% NaCl solution. The results showed that

the values of corrosion rate and corrosion potential decreased with the application of the electrochemical precipitation coating more than the same values by using the paint coating of the steel storage tank at 3.5 % Chloride.

Sada, et al., (2016). The protection system of the impressed current has been studied experimentally and theoretically. Form ICCPs were installed for bare tubes of carbon core (new and old) immersed in brine. The effect of changing several parameters of salt water on the cathodic protection current such as temperature, conductivity, and ventilation flow rate was studied. Results have shown that an increase in the temperature, conductivity and flow rate leads to an increase in the protection current required to achieve adequate protection and also indicated that the protection current required for the old tube is greater than the cathode current of the new tube in the same environmental conditions of the brine solution. The experimental data for the prototype was used to build a model for the identification of ICCPs using Adaptive Neural Inference (ADN) ANFIS technique with MATLAB R2015a software to set the potential of the tube segment at the desired protection level.

Lim, C. M. (2017). discussed the reducing of the wear rate of a ship's hull that needs a high budget for maintenance and repair by introducing cathodic protection for sacrificial anode SACPs. Zinc anode and light carbon steel vessel hull are used. Zinc is more corrosive than carbon steel, thus reducing the corrosion rate of the hull. The environmental effects in sea water, such as temperature and sea water velocity, were studied, and the effect of all these factors on the corrosion performance of zinc coupled steels and light carbon steels was studied. The results of the experiment showed that zinc and carbon steel were coupled through the method of attachment to the screws at 45 ° C; 200rpm has the highest wear rate of 1.202 x 10⁻²mm / year

compared to the lowest wear rate of 1.061×10^{-4} mm / year of casting method; 45 ° C; 0 revolutions per minute.

Khan, et al. (2018). Focused on mitigating the corrosion rate of buried underground pipelines and natural gas lines by using three different DC sources (generator transformer, heat generator, and solar power system) for a specific period of time in two locations in Balochistan province of Pakistan with an ICCP system, where the regions differ in terms of climate resistance and soil resistance. The experimental results showed that the solar energy system is a promising solution in reducing and controlling the rate of corrosion because it tends to provide more stable DC power for the ICCP system in hot and cold temperatures and in high and low resistance environments. The proposed research will assist companies and industries in selecting the appropriate type of external DC source while designing an ICCP system according to the climate, versatility, output power density, and cost efficiency of corrosion protection for underground pipelines.

Hanif, et al. (2019). Compared the possible differences in cathodic protection techniques (the Impressed current current method and the sacrificial anode method). A sample of soft steel was used to protect it from corrosion and the zinc anode for the sacrificial anode method, a constant current source was applied. The sample is exposed to different concentrations of NaCl. Experiment have shown that the corrosion of mild steel is higher by the sacrificial anode method than by the directed current method. Therefore, the direct current technique was considered effective to maintain the corrosion rate at the lowest level. It is also evident that the rate of metal corrosion is related to the concentrations of NaCl. The higher the concentration, the higher the rate of corrosion. Therefore, we use the direct current method to supply a higher direct current as it is suitable in highly corrosive environments.

Adetunji, et al. (2019) Investigated protecting of the underground buried mild steel pipes by the ICCP method by using solar cells as a rectifier for continuous electricity supply to protect the structures. The tubes were buried in two separate locations; X and Y. Site X buried the tubes without protection, while Site Y cathodic protection was applied to the tubes for a period of 40 days. It was concluded that the buried tubes in position Y were less wear and the tube-soil potential of PSP measured within the cathodic protection standards adopted by NACE is -850 mV with respect to the copper / copper sulfate saturated electrode. The tubes were corroded in position X and the PSP value is less than -850 mV. Physical examination and fine fixture of the tubes indicated visible evidence of corrosion on the tubes buried without protection, and this did not appear on the tubes buried under ICCP using solar cells. All PSP values less than -2000 mV were obtained indicating a lack of overprotection.

Khomwan, et.al. , (2019). Illustrated the sacrificial anode method is illustrated to prevent corrosion of the wiped concrete structures by using zinc metal anodes covered with two types of highly alkaline activation mortars, which sacrifice themselves to protect the corrosion of reinforcing steel. As this slurry helps the total cathodic reaction to protect the armature efficiently. Focus on the performance of new sacrificial anodes installed in concrete saws, slabs, and concrete water tanks in order to explore the anti-corrosion performance of NACE, ISO and ASTM standards. The anode life of 28 days and 365 days were applied to ensure that the slurry activation time is approved. The experimental results showed that the anode polarized the rebar with a large capacity in relation to the posts and the concrete slabs. For the water tank test results, two different types of concrete were performed with exposure to chloride solution and evaluated using near interval potential maps. The results showed good compatibility with enhanced structural durability.

BAWA, et al (2020) Presented the importance of choosing the suitable anode material for the impressed current cathodic protection system. Four anodes of different materials were used to evaluate their performance

(Aluminum 90.6% , Copper 9.4% \ Copper 90% , Aluminum 10% \ Copper 95% , Aluminum 5% \ Lead 100%). The aggressive environment was simulated by saturating the soil with NaCl solution to form corrosive cells. In each of the four corrosion cells, a well-polished steel tube was buried to remove all traces of the corrosion products in order to properly obtain the protective potentials and anodes and placed in wooden boxes. In each cell the tube-soil potential reading was taken using the copper / copper sulfate reference electrode and the changes in the environmental pH and temperature are reported throughout the experiment period of the four corrosion cells. It was concluded that the lead anode has a low dissolution rate and was the ideal material among other materials for the ICCP system, and it is cheap and available for buried and submerged structures in aggressive environments.

Tables (2-8) and (2-9) show a summary of previous studies by SACP and ICCP researchers for cathodic protection systems.

Table (2-8): Summary of experimental studies of the ICCPs method

Authors	Year	Important result
Tao, D., et.al.	2005	Studied on reducing the corrosion rate of phosphate mills in an acidic medium at pH (2-4). The experimental results were a decrease in the corrosion rate the more effectively the pH was increased.

Ajeel, et.al.	2008	Design a cathodic protection system to prevent corrosion of a carbon steel pipe in various operating conditions in terms of temperature, change of distance between pipe and anode, salt concentration and pH of the solution. Experimental results showed that the protection current density increases with increasing concentration, temperature and pH and slightly increases with increasing distance between the anode and cathode.
Abud Al-Rahman, H. M.	2009	The effect of environmental resistance and negative electrode distance on the protective current density of bare and sheathed steel tubes using graphite anode was shown. The CP of the coated tube is observed to be very low compared to that of the bare tube
Shamsuri, Siti Rahmah.	2010	Use coated and uncoated carbon steel samples and determine the influence of soil properties and contents on its corrosion behaviour. The results showed that the corrosion rate increases significantly at a level lower than pH (1 to 2), and the density of the corrosion current increases with temperature, in addition to that the uncoated eye has a higher corrosion rate than the coated one.
Jabur S., A	2014	The protection of soil-immersed carbon steel tube and the influence of factors on tube corrosion protection, such as the location of the anode (distance and depth), soil resistance (wet and dry), tube conditioning (coated and uncoated), and distribution of potentials and currents along the tube (cathode). The result was an increase in the protection current

		with a decrease in the environmental resistance and an increase in the distance between the anode and the cathode of uncoated tubes and a higher corrosion rate than coated tubes.
Ali, A.	2014	studied the downstream cathodic protection system of a 100 cm long carbon steel tube buried in a wooden case immersed in soil. The effect of factors on protecting the pipe from corrosion, such as anode location (distance and depth), soil resistance (wet and dry), tube conditioning (coated and non-coated), the distribution of potentials and currents along the tube (cathode) and the amount of current required were investigated to achieve cathodic protection.
AS, A., KC, A., & JJ, A	2015	The tube was buried for 60 days in moderate soil and cathodic protection was applied. The results observed that the corrosion rate was significantly reduced after the application of cathodic protection.
Sada, et al.	2016	The effect of changing several brine parameters on the cathodic protection current such as temperature, conductivity and ventilation flow rate of an uncoated tube immersed in brine has been studied experimentally and theoretically. The results showed that the increase in temperature, conductivity and flow rate leads to an increase in the protection current required to achieve adequate protection, and also indicated that the required protection current for the old tube is greater than the cathode current for the new tube under the same environmental conditions of brine. The experimental and theoretical results are in agreement.

Khan, et al.	2018	Focuses on mitigating the corrosion rate of underground pipelines and buried natural gas lines by using three different DC sources (transformer generator, heat generator, and solar system). The results showed that the solar power system is a promising solution in reducing and controlling the rate of corrosion because it tends to provide more stable DC power to the ICCP system in hot and cold temperatures and in high and low resistance environments.
Adetunji, et al.	2019	The protection of the mild steel tubes during burial was investigated in two locations (a site without protection application and a site with protection). Physical examination and careful tube fitting showed visible evidence of corrosion of unprotected buried tubes, and this was not seen on tubes buried under ICCP using solar cells.
BAWA, et al	2020	The anode type was clarified using four types of anodes (aluminum 90.6%, copper 9.4%, copper 90%, aluminum 10%, copper 95%, aluminum 5%, lead 100%) by saturating the soil with sodium chloride solution to form corrosive cells. It was concluded that the lead anode had a low dissolution rate and was the ideal material among other materials for the ICCP system, which is cheap and available for buried and submerged structures in aggressive environments.

Table (2-9): Summary of experimental studies of the SACPs method

Authors	Year	Important result
Hameed, et.al.	2007	These studies used zinc anode in seawater 4% NaCl, and the solution conditions were changed from temperature, pH, velocity of solution flow and time. The experimental results showed that the rate of zinc consumption in a weight loss method increases with the increase in temperature, time and velocity of the solution and decreases with the increase in the pH of the solution
Rashid, K. T.	2009	This researcher studied the effect of temperature, different sodium chloride concentrations and mixing speed on the cathodic protection current values using magnesium anode. It was found that the speed of mixing different solutions and the temperature increase the conductivity of the solution and allow the passage of a higher current from the anode to the cathode.
Zedin, et.al.	2015	Application of protection to a tank using anodes and effective coating in 3.5% brine. The results showed that the values of corrosion rate and corrosion potential decreased with the application of paint and cathodic protection.
Lim, C. M.	2017	It discussed the protection of ship hulls using zinc anode and the study of environmental influences in sea water such as temperature and sea water velocity and studying the effect of all these factors on the corrosion performance of steel. The results showed a significant decrease in the corrosion rate.

Hanif, et al.	2019	Use a sample of steel and expose the sample to different concentrations of NaCl and compare potential differences in cathodic protection techniques (impact current method and sacrificial anode method). Experience has shown that the corrosion of mild steel is higher by the sacrificial anode method than by the Impressed current method. Therefore, DC technology was considered effective to keep the corrosion rate at a minimum level.
Khomwan, et.al	2019	Zinc anodes covered with two types of high alkaline activation slurry were used to protect concrete structures. Experimental results showed that the positive electrode attracts steel reinforcement with a large amplitude for concrete supports and slabs.

Chapter Three

Experimental Work

This chapter deals with the cathodic protection system that is applied to protect a piece of bare carbon steel plate using ICCP and SACP. The experiments were performed at various variables such as salt concentration, temperature, and pH in addition. Graphite was used as an anode in ICCP, and Aluminum alloy was used as an anode in SACP. In ICCP different potentials (-700, -900, -1000 and -1200) mv with respect to the copper / copper sulfate reference electrode are applied.

3.1 Experimental Work

3.1.1 Cathodic Protection Rig and Tests Devices

The cathodic protection system rig is composed of the following components:

- **Cathode**

Using a metal sheet of carbon steel plate (Cs) A36 according to ASTM standards, with dimensions of (100 x 10 x 6) mm. The sample was taken from Karbala refinery. The chemical composition of carbon steel is listed as shown in Table. (3-1).

Table (3.1): Chemical Composition of Carbon Steel plate (A36).

C %	Si %	Mn%	P%	S%	Cu%	Fe%
0.25	0.4	0.00	0.04	0.05	0.2	99.06

- **Anode**

1-The electrode used in ICCP is Graphite with dimensions of (100 x 20 x 15) mm.

2- A plate of Aluminum alloy was with dimensions of (100 x 10 x 10) cm is used in SACP. The chemical composition of the alloy is given in table (2-3).

Table (3.2): Chemical Composition of Aluminum alloy

AL%	Mn%	Remainder
99.31	0.680	0.01

- **The Applied Solution**

The solution is prepared experimentally by adding different weights of NaCl (0.5, 1.5 and 3) g/L of distilled water from the desalination plant.

- **Glass Bath**

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 ... etc...

- **Power supply**

DC power supply is used to apply voltage as shown in figure (3.1e).

- **Reference electrode**

The electrode used is copper / copper sulfate to measure the potential of working electrode (the cathode) as shown in figure. (3.1b).

- **Conductivity Meter**

SKEIDO digital device B07SDC79H1 used to measure the level of receptive pH (PH), electrical conductivity (EC), total mineral dissolved in water (TDS) and temperature simultaneously.

- **Sensitive Balance**

A digital scale from SF-400 is used to measure the weight of NaCl used in this work. The capacity of the device is 5 kg, shown in Figure (3.1c).

- **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 as shown in the figure. (3.1d).

- **Thermometer**

A glass thermometer (0-100) °C was placed in the glass bath to measure the temperature of the solution.

- **Portable Heater**

B.L.A type GME-B.L. A is used to heat the solution and control the temperature during the experiment.



(a) Conductivity Meter



(b) Reference electrode



(c) Sensitive Balance



(d) Voltmeter and Ammeter



(e) D.C Power Supply

Figure (3.1): The experiment units

3.1.2 The Experimental Procedure

3.1.2.1 Preparing the Piece of Steel

The metal piece (cathode) must be cleaned before immersing it in a corrosive solution using emery paper grades (TJ113 (JB-5) A320), then it is dipped in alcohol for two minutes and then dried with a clean cloth (tissue paper). Fig. (3.2) shows the cathode before and after cleaning.

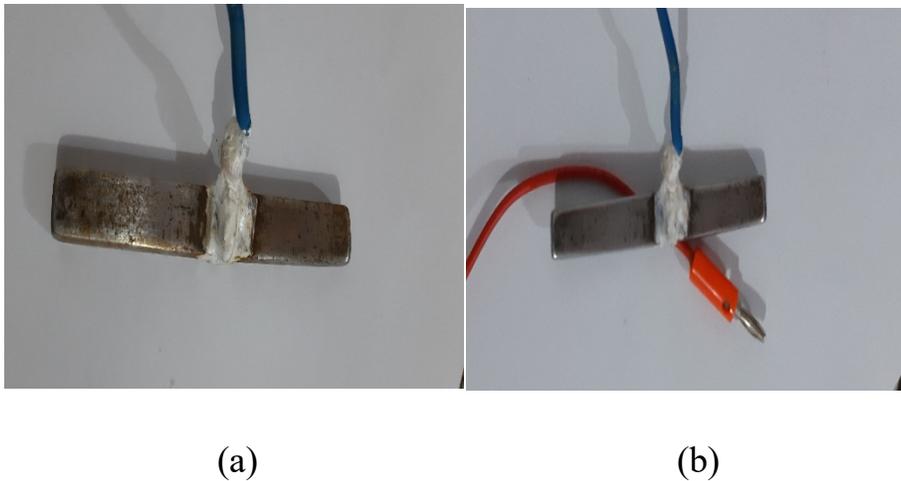


Figure (3.2): Specimen (a) before cleaning (b) after cleaning.

3.1.2.2 Connection

After cleaning the surface of the structure to be protected, we use copper wires (cables) are used with a diameter of 2 mm, which are connected to the cathode surface and the anode surface by welding. One of the copper conductors is for DC power supply through the negative terminal (drain point), and the other is for the reference electrode (test point).

These connection points are coated with a thermoplastic silicone adhesive to prevent any error caused by the contact points being exposed to the environment.

3.1.2.3 Design of the Cathodic Protection System

The CP system is established as shown in figures (3.3), (3.4) and (3.5). Both the anode and the cathode are suspended using a plastic holder and the electrodes are submerged in the salt solution. The anode and cathode are immersed at a depth of (45) mm above the bottom and (25) mm below the surface of the solution. The distance between the cathode and the anode is 500 mm. All devices used inside the glass aquarium are non-metallic to avoid stray currents affecting the measurement value. In this test, a copper / copper sulfate reference electrode was used close to the cathode surface to avoid the IR drop. This setup is applied in each experiment in addition to washing the glass basin and its accessories with distilled water to ensure that there are no traces of the previous test. Then it is filled with the prepared solution ready for new operation.

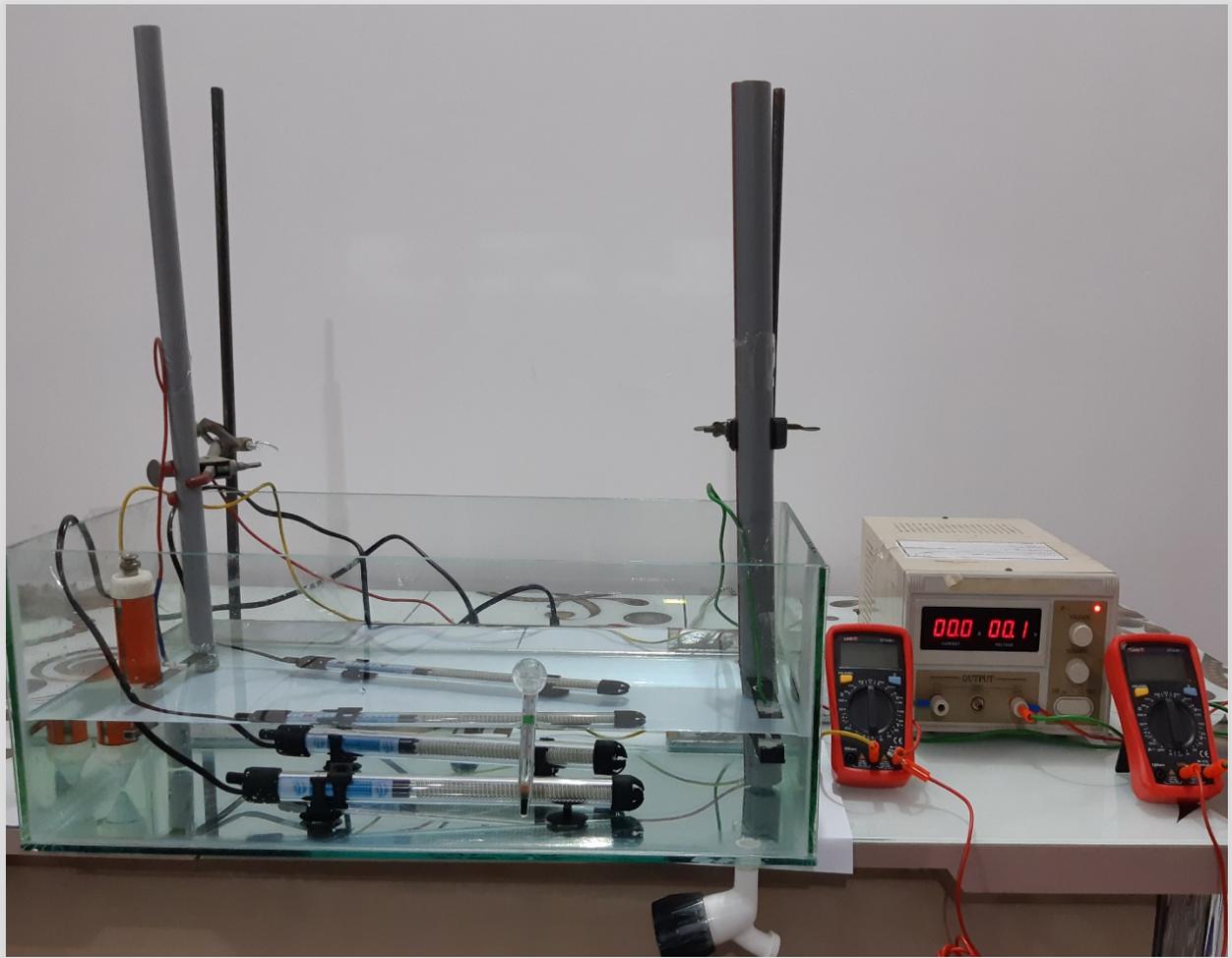
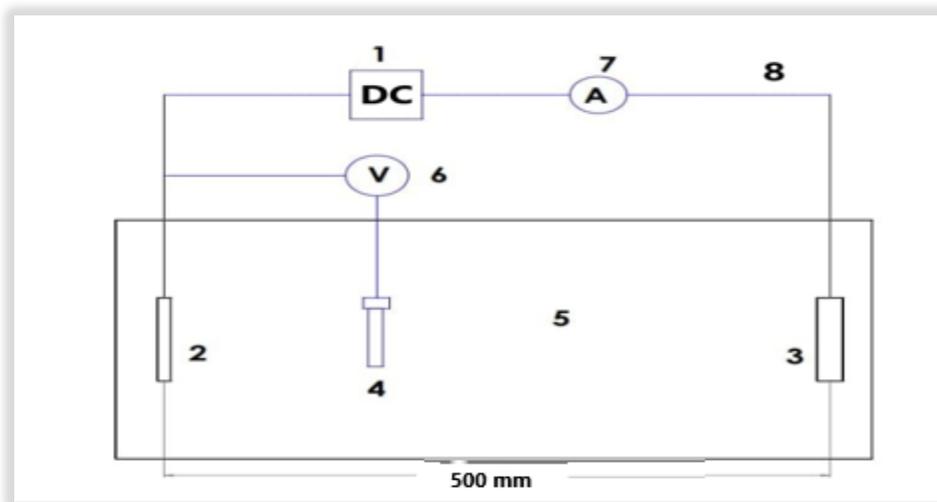
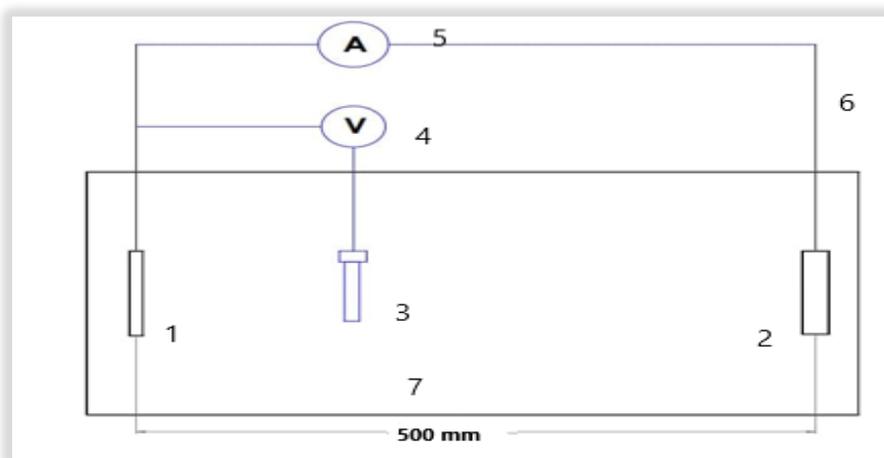


Figure (3.3): Photo of The Installed ICCP System.



1.DC power supply	3.anode	5.solution	7. ammeter
2.cathode	4.reference electrode	6. voltmeter	8. connecting wires

Figure (3.4): Schematic Diagram of the Installed ICCP system



1. cathode	3.reference electrode	5.ammeter	7.solution
2.anode	4. voltmeter	6. connecting wires	

Figure (3.5): Schematic Diagram of the Installed SACP system

3.1.2.4 CP System Measurements

Four solution variables have been studied. The first variable is the conductivity of the solution by adding different weights of NaCl (0.5, 1.5 and 3) g/L of distilled water in the basin. The second variable is changing the temperature of the solution (20, 30 and 40) °C using an electric heater placed inside the basin. The third variable is the pH of the solution where an acidic solution with a value of 4 is obtained by adding an acid (sulfuric acid) and adding a base (sodium hydroxide) to change the pH to 10. The fourth variable is the cathode voltage (sample) obtained by applying the current from the power source (-700, -900, -1000 and -1200) mV with respect to the copper / copper sulfate reference electrode. Then the current is measured for two hours and a 30-minute interval between two readings. Whereas for SACPs, a power supply is not used here because the aluminum alloy that is used in the system as the anode is the source to provide sufficient electrons to accomplish the protection. The current and voltage are read every 15 minutes for two hours. The same procedures are used in the ICCP method for cleaning the structure to be protected and cleaning the basin before and after each experiment.

Chapter Four

Results and Discussion

The experimental results in the current work obtained from the implementation of the ICCP and the SACP methods show the effect of variation in temperature, conductivity and the pH of the solution on the protection current through a series of experiments conducted at different electrolyte-structure potentials (-700, - 900, - 1000, -1200) mV.

4.1 The Influenced of Salt Concentration on The Protection Current Density

*** By applying ICCPs method**

Figures (4-1) to (4-3) show an increase in protection current density with increasing the concentrations of sodium chloride dissolved in water at different pH and temperatures of the solution. It is increase in solubility of sodium chloride in water leads to an increase in conductivity of the solution due to the increase in the decomposition of sodium chloride into positive and negative ions dissolved in the solution (Cl^- , Na^+), in addition to the hydrolysis ions and the decomposition of the added acid or the added base to change the acidity of the solution.

The more decomposition means the more ions need electrons in order to convert to atoms and molecules, and some of them are precipitated in the solution and hence increase the conductivity of the solution and, consequently, an increase in the speed of transmission of electric current, and therefore an increase in the cathodic protection current.

Higher concentration of the salt provides more negative chloride ions. The aquatic environments that contain chloride content are among the most corrosive

environments, in addition to the presence of oxygen ions in the solution (especially for open systems), this means that the presence of these ions has a direct relationship with high rates of corrosion, so the presence of dissolved chloride ions and dissolved oxygen ions does accelerate the corrosion rate. The higher the amount of dissolved salt, the higher the corrosion rate, and therefore we need a higher cathodic protection current.

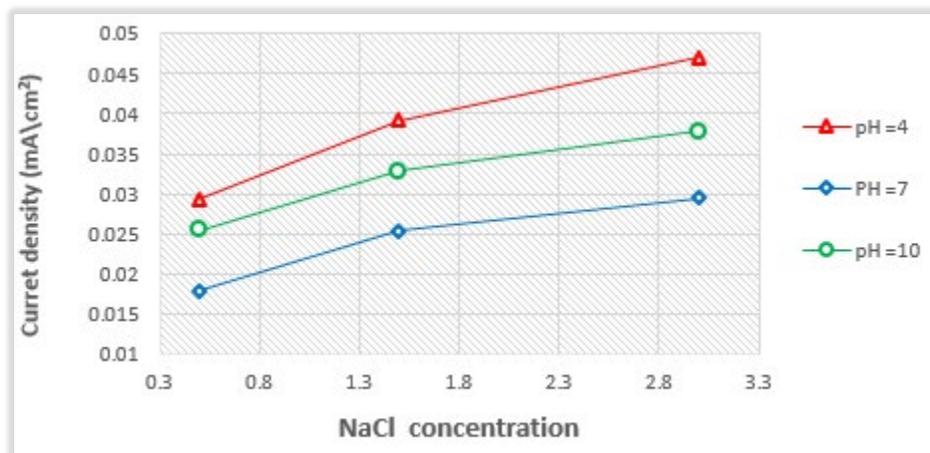


Figure (4-1): Current density vs NaCl concentrations at different values of pH, an applied voltage of -700 mv and a solution temperature of $T = 20\text{ }^{\circ}\text{C}$.

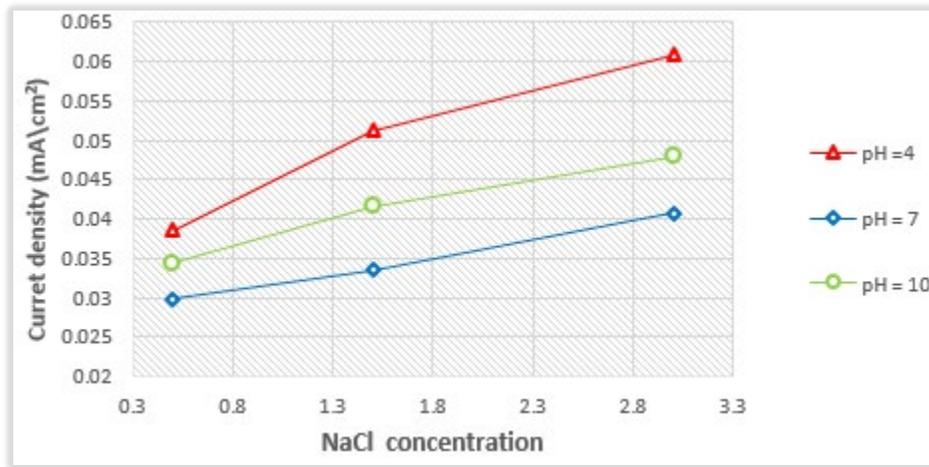


Figure (4-2): Current density vs NaCl concentrations at different values of pH, an applied voltage of -700 mv and a solution temperature of $T=30\text{ }^{\circ}\text{C}$.

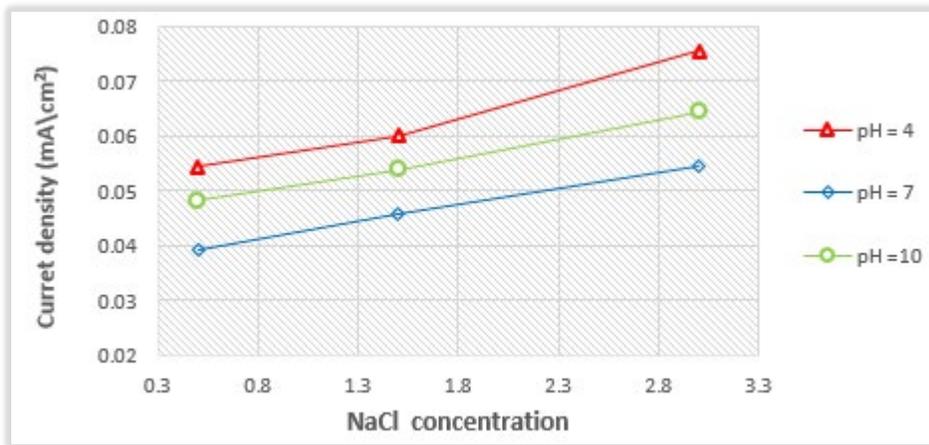


Figure (4-3): Current density vs NaCl concentrations at different values of pH, an applied voltage of -700 mv and a solution temperature of $T=40\text{ }^{\circ}\text{C}$.

Similar trend is obtained at the solution temperature of 20, 30 and 40 $^{\circ}\text{C}$ and applied voltages of -900, -1000 and -1200 mv.

All experimental data between salt concentration and current density were included according to the listed tables from (4-1) to (4-3) with different temperatures and pH. Because they have the same behavior as shown in the figures.

Table (4-1): Current density vs NaCl concentrations at different values pH, different applied voltages and a solution temperature of T= 20 °C.

Concentration (g/L)	Current density at applied voltage -700 mv			Current density at applied voltage -900 mv		
	pH =4	pH =7	pH =10	pH =4	pH =7	pH =10
0.5	0.029	0.018	0.025	0.038	0.02	0.034
1.5	0.039	0.025	0.033	0.049	0.031	0.042
3	0.047	0.029	0.038	0.053	0.037	0.046
Concentration (g/L)	Current density at applied voltage -1000 mv			Current density at applied voltage -1200 mv		
	pH =4	pH =7	pH =10	pH =4	pH =7	pH =10
0.5	0.044	0.029	0.038	0.394	0.2618	0.308
1.5	0.053	0.034	0.049	0.489	0.331	0.394
3	0.057	0.039	0.049	0.613	0.457	0.510

Table (4-2): Current density vs NaCl concentrations at different values pH, different applied voltages and a solution temperature of T= 30 °C.

Concentration (g/L)	Current density at applied voltage -700 mv			Current density at applied voltage -900 mv		
	pH =4	pH =7	pH =10	pH =4	pH =7	pH =10
0.5	0.039	0.030	0.034	0.049	0.034	0.038
1.5	0.051	0.033	0.042	0.064	0.044	0.055
3	0.061	0.041	0.048	0.078	0.051	0.064
Concentration (g/L)	Current density at applied voltage -1000 mv			Current density at applied voltage -1200 mv		
	pH =4	pH =7	pH =10	pH =4	pH =7	pH =10
0.5	0.059	0.037	0.044	0.500	0.346	0.416
1.5	0.073	0.048	0.060	0.564	0.417	0.469
3	0.084	0.056	0.072	0.633	0.500	0.594

Table (4-3): Current density vs NaCl concentrations at different values pH, different applied voltages and a solution temperature of T= 40 °C.

Concentration (g/L)	Current density at applied voltage -700 mv			Current density at applied voltage -900 mv		
	pH =4	pH =7	pH =10	pH =4	pH =7	pH =10
0.5	0.054	0.039	0.048	0.057	0.034	0.050
1.5	0.060	0.046	0.054	0.078	0.048	0.062
3	0.075	0.055	0.064	0.093	0.061	0.079
Concentration (g/L)	Current density at applied voltage -1000 mv			Current density at applied voltage -1200 mv		
	pH =4	pH =7	pH =10	pH =4	pH =7	pH =10
0.5	0.063	0.039	0.049	0.549	0.380	0.467
1.5	0.082	0.054	0.069	0.647	0.494	0.590
3	0.102	0.074	0.087	0.738	0.554	0.614

Figures indicate that the higher the salt concentration in the solution, the higher the cathodic protection current density with a constant distance of 50 cm between the anode and the cathode under different operating conditions, where the conductivity is low (low content chloride ion), the iron ion at the anode and the hydroxyl ion at the cathodes combine to form an insoluble and unstable protective layer on the surface of the metal (ferrous hydroxide), a corrosion product, and the possibility of combining with negative chloride ions to form (ferrous chloride) for this reason, when the conductivity increases, dissolved oxygen ions reach the surface of the negative electrode and thus combine with water to form hydroxyl ion, which means higher protection current is needed.

The current densities of the cathodic protection with protection voltages (-700, -900, -1000) mV are approximately close to each other, as the voltage from a DC source at range of 2 to 2.5 V was applied, and about 3.5 V from a DC source to obtain a protection voltage - 1200 mV. It is found that the higher the DC voltage

value, the higher the wear rate and the higher the required cathodic protection current. At a voltage of -700 millivolts at different temperatures, the highest protection current is at pH = 4 due to the abundance of hydrogen ions in acidic environments and these ions need electrons from the continuous source to turn into hydrogen gas and also with increasing temperatures that lead to an increase in the movement of ions within the solution reaches the surface of the structure for the reaction, which increases the required protection current at $T = 40\text{ }^{\circ}\text{C}$. At all different protection voltages, the highest possible protection current is obtained.

The protection current density at the protection voltage -700, -900, -1000 mV is close to each other, while the protection current density at -1200 mV is three times more.

Figure (4-4) shows the values of the current density at temperature and pH increases with different values of the applied voltage, and at the applied voltage -1200 millivolts, the current density in it is ten times the values of the current density at the voltages shown in the figure.

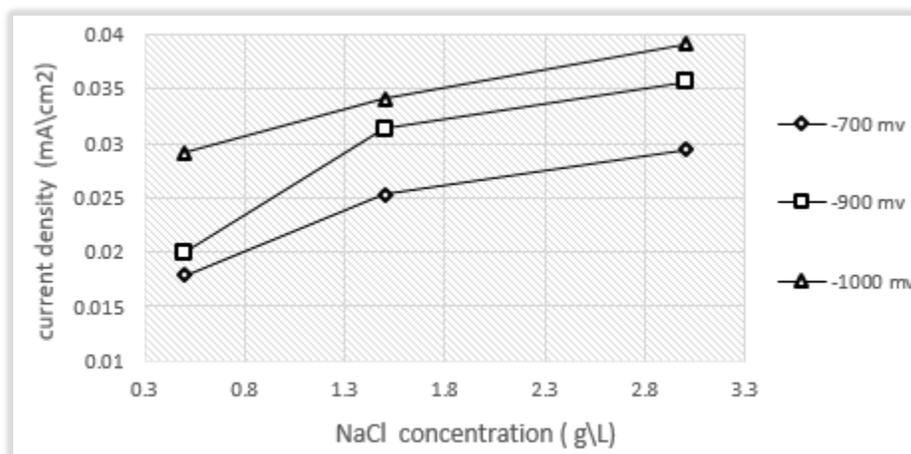


Figure (4-4): Current density vs NaCl concentrations at different applied voltage, a solution pH =7 and temperature $T = 20\text{ }^{\circ}\text{C}$.

*** By applying SACP's method**

Figures (4-5) to (4-7) show an increase in the density of the protection current with increasing concentrations of sodium chloride dissolved in water at different pH and temperatures of the solution as a result of increasing the decomposition of sodium chloride into positive and negative ions dissolved in the solution. The greater the decomposition, the greater the need for ions to electrons to turn into atoms and molecules, and some of them are precipitated in the solution and thus increase the conductivity of the solution and thus increase the speed of transmission of electric current, and thus increase the cathodic protection current.

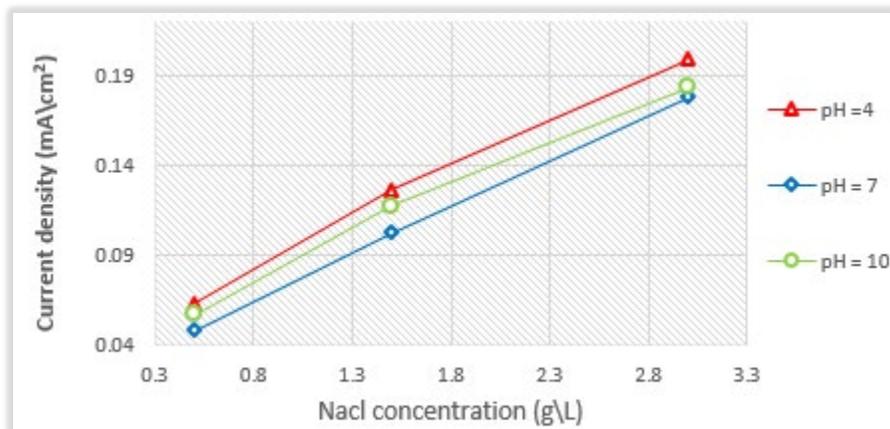


Figure (4-5): Current density vs NaCl concentrations at different values of pH and a solution temperature of $T = 20\text{ }^{\circ}\text{C}$.

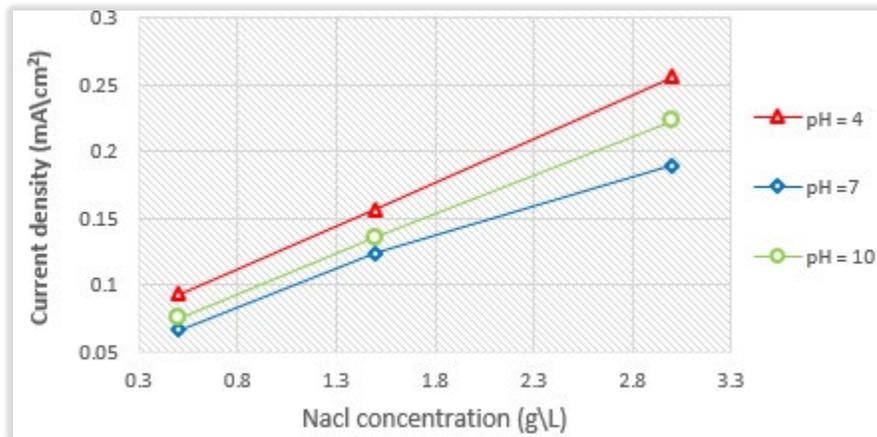


Figure (4-6): Current density vs NaCl concentrations at different values of pH and a solution temperature of $T=30\text{ }^{\circ}\text{C}$.

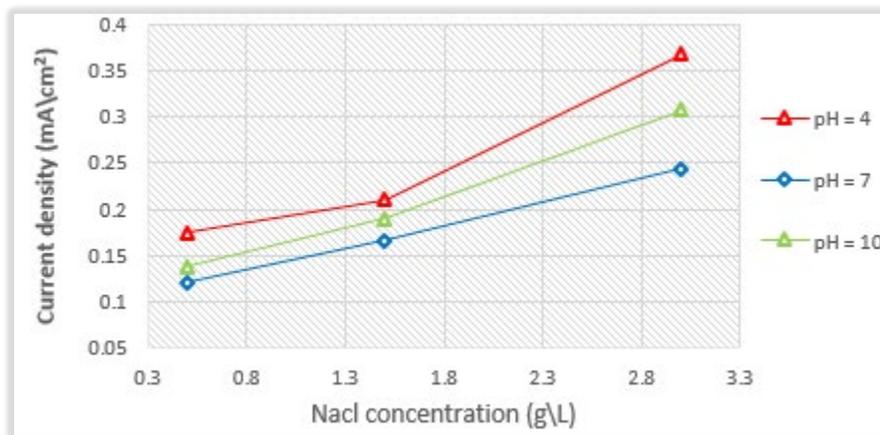


Figure (4-7): Current density vs NaCl concentrations at different values of pH and a solution temperature of $T=40\text{ }^{\circ}\text{C}$.

The higher the temperature, the higher the current density. And in acidic media, it is the highest protection current needed by the system.

All experimental values for the protection current density with different salt concentrations are shown in Table (4-4). It shows with an increase in concentration

and temperature, the protection current density increases, and the current density increases with the decrease in pH.

Table (4-4): Current density vs NaCl concentrations at different values of pH, and at different values temperature.

Concentration (g\L)	Current density (mA\cm ²) at pH=4			Current density (mA\cm ²) at pH=7			Current density (mA\cm ²) at pH=10		
	T=20°C	T=30°C	T=40°C	T=20°C	T=30°C	T=40°C	T=20°C	T=30°C	T=40°C
0.5	0.063	0.093	0.175	0.048	0.066	0.120	0.057	0.075	0.139
1.5	0.127	0.157	0.211	0.102	0.123	0.166	0.117	0.136	0.190
3	0.199	0.256	0.367	0.178	0.190	0.244	0.184	0.224	0.307

4.2 The Effect of pH on the Protection Current Density

* by applying ICCPs method

The cathodic protection current or corrosion rate increases with decreasing pH at different conductivities and temperatures. In acidic environments, the presence of hydrogen ions significantly in these environments, they need more electrons. Corrosion products are usually formed as a film on the metal surface, in an acidic medium this film dissolves and the metal is in direct contact with its the environment and the corrosion rate increases. In the basic medium, the corrosion rate decreases due to the formation of the membrane due to the presence of alkali and dissolved oxygen. Figures (4-8) to (4-10) show the influence of pH on the protection current density and at different concentration of salt (0.5, 1.5, 3) % and temperature of (20, 30 and 40) °C, with a constant distance between the anode and cathode, and at different values of the protection voltage (-700, -900, -1000, 1200) mv. It is seen that the cathodic current densities at pH (4 and 10) are more than that at pH = 7. The

required cathodic current density at pH (4 and 10) has almost similar trend and values due to the increase in hydrogen evolution in both cases as a result of the hydrogen reduction reaction in acidic media and the water reduction reaction in alkaline media. Which means it needs a higher protection current density in the acidic medium than in the basic medium, followed by the neutral media. The higher the NaCl concentration and temperature of the solution, the higher the current density. The temperature effect is higher and more pronounced than that of pH. In an acidic environment, the predominant reaction is the reduction of hydrogen ions. The structure needs to withdraw more electrons provided by the direct current source, so the hydrogen ion needs one electron to turn into an atom and the atoms combine to form a hydrogen molecule and the hydrogen molecules are bound which leads to the liberation of the hydrogen gas bubble. So, it needs higher current to protect the structure. In the basic medium, hydroxyl ions are abundantly present in the solution due to the hydrolysis of water and the decomposition of sodium hydroxide (the added base of the solution). So, the dominant reaction is the oxygen reduction reaction, which leads to an increase of hydroxyl ions at the interface of the electrolyte structure. So, the dominant reaction is the oxygen reduction action, which leads to an increase of hydroxyl ions at the interface of the electrolyte structure and increase the pH at the interface of the metal which leads to decrease applied potential to protect the metal.

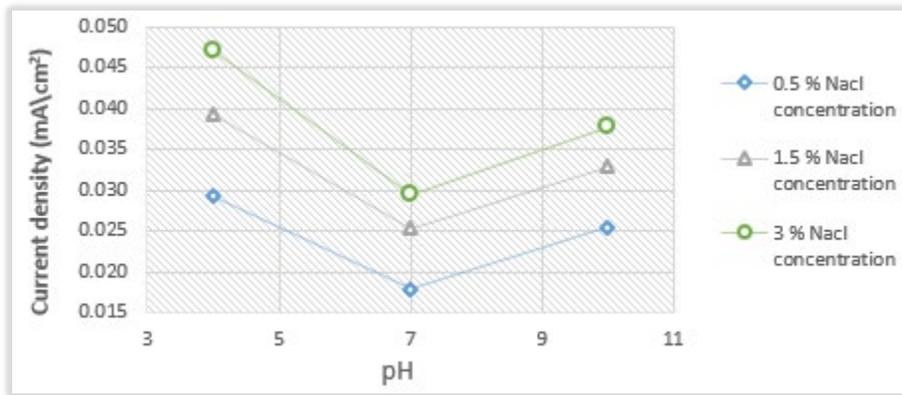


Figure (4-8): Current density vs. pH values at different NaCl concentration -700 mv and T=20 °C.

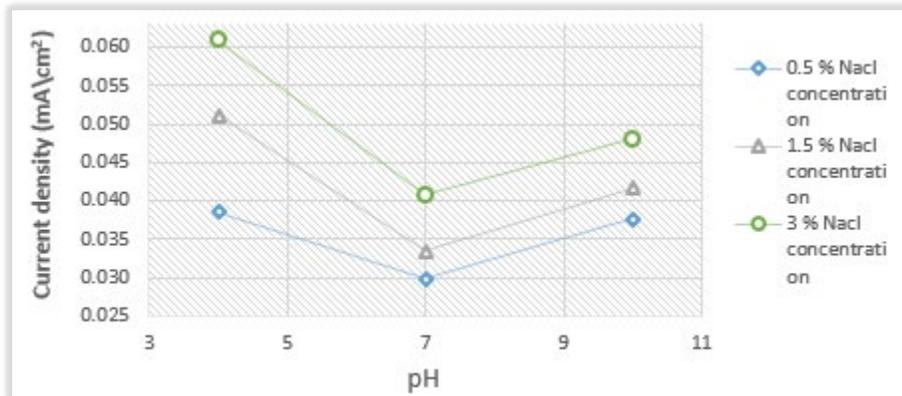


Figure (4-9): Current density vs. pH values at different NaCl concentration -700 mv and T=30 °C.

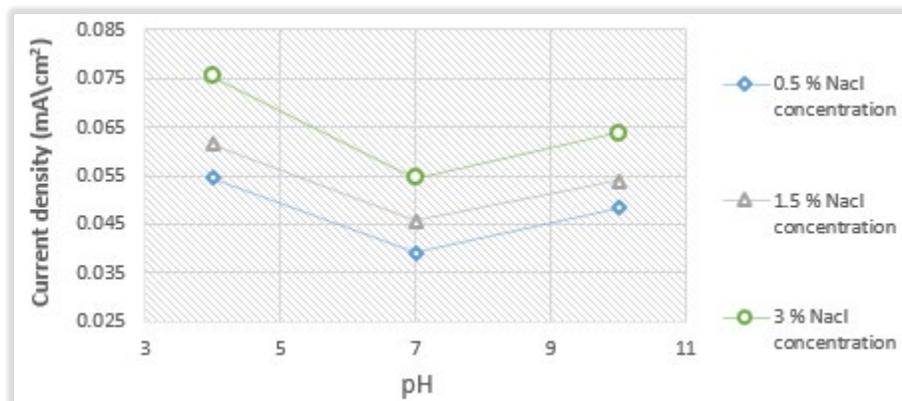


Figure (4-10): Current density vs. pH values at different NaCl concentration -700 mv and T=40 °C.

A similar trend is obtained at a solution temperature of 20, 30 and 40 °C and an applied voltage of -900, -1000, -1200 mV. Figure (4-11) shows the effect of current density at applied voltages except for the voltage -1200 millivolts because the protection current is ten times higher than the other voltages.

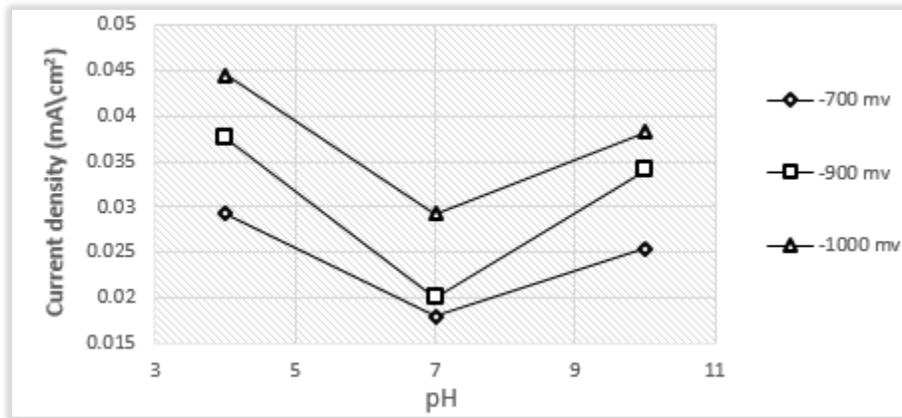


Figure (4-11): Current density vs pH values at NaCl concentrations at different applied voltage, 0.5% NaCl concentration and temperature $T= 20\text{ }^{\circ}\text{C}$.

All experimental data for each of the applied temperatures and voltages -900, -1000 and -1200 millivolts are shown in Tables (4-5) to (4-6).

Table (4-5): Current density vs pH values at different concentrations, different applied voltages and a solution temperature of T= 20 °C.

pH	Current density at applied voltage -700 mv			Current density at applied voltage -900 mv		
	0.5 %NaCl	1.5 %NaCl	3 %NaCl	0.5 %NaCl	1.5 %NaCl	3 %NaCl
4	0.029	0.039	0.047	0.038	0.049	0.053
7	0.018	0.025	0.029	0.020	0.031	0.036
10	0.025	0.033	0.038	0.034	0.042	0.046
pH	Current density at applied voltage -1000 mv			Current density at applied voltage -1200 mv		
	0.5 %NaCl	1.5 %NaCl	3 %NaCl	0.5 %NaCl	1.5 %NaCl	3 %NaCl
4	0.044	0.053	0.057	0.394	0.489	0.614
7	0.029	0.034	0.039	0.262	0.331	0.457
10	0.038	0.048	0.049	0.308	0.394	0.510

Table (4-6): Current density vs pH values at different concentrations, different applied voltages and a solution temperature of T= 30 °C.

pH	Current density at applied voltage -700 mv			Current density at applied voltage -900 mv		
	0.5 %NaCl	1.5 %NaCl	3 %NaCl	0.5 %NaCl	1.5 %NaCl	3 %NaCl
4	0.039	0.051	0.061	0.049	0.064	0.077
7	0.030	0.033	0.041	0.034	0.044	0.051
10	0.038	0.042	0.048	0.038	0.055	0.064
pH	Current density at applied voltage -1000 mv			Current density at applied voltage -1200 mv		
	0.5 %NaCl	1.5 %NaCl	3 %NaCl	0.5 %NaCl	1.5 %NaCl	3 %NaCl
4	0.059	0.073	0.084	0.524	0.591	0.633
7	0.037	0.048	0.056	0.363	0.436	0.524
10	0.044	0.060	0.072	0.436	0.491	0.622

Table (4-7): Current density vs pH values at different concentrations, different applied voltages, and a solution temperature of T= 40 °C.

pH	Current density at applied voltage -700 mv			Current density at applied voltage -900 mv		
	0.5 %NaCl	1.5 %NaCl	3 %NaCl	0.5 %NaCl	1.5 %NaCl	3 %NaCl
4	0.054	0.061	0.075	0.057	0.078	0.093
7	0.039	0.046	0.055	0.038	0.048	0.061
10	0.048	0.054	0.064	0.050	0.062	0.079
pH	Current density at applied voltage -1000 mv			Current density at applied voltage -1200 mv		
	0.5 %NaCl	1.5 %NaCl	3 %NaCl	0.5 %NaCl	1.5 %NaCl	3 %NaCl
4	0.063	0.082	0.103	0.575	0.678	0.773
7	0.039	0.054	0.074	0.398	0.517	0.580
10	0.049	0.069	0.087	0.490	0.618	0.644

At pH = 7, the current density has values between (16-39) $\mu\text{A}/\text{cm}^2$ at 20°C, and increase to (30-56) $\mu\text{A}/\text{cm}^2$ at 30°C with increasing the solution temperature to 40°C about (39-74) $\mu\text{A}/\text{cm}^2$ and increasing the protection voltages - 700, -900 and -1000 mv, a higher current density is required due to the increase in the velocity of diffusion and the movement of ions with increasing temperature and conductivity of the solution and thus an increase in the reaction rate at the cathode. Increasing the applied voltage to -1200 mv lead to increase from 250 $\mu\text{A}/\text{cm}^2$ to 580 $\mu\text{A}/\text{cm}^2$ with temperature from 20°C to 40°C .

while pH = 4, it needs a higher current density between (29-57) $\mu\text{A} / \text{cm}^2$ at a temperature of 20 ° C, and increase the protection current to (38-84) $\mu\text{A}/\text{cm}^2$ at 30 ° C, the protection current is between (36-80) $\mu\text{A}/\text{cm}^2$ and at a temperature of 40 ° C, ranging between (54-103) $\mu\text{A}/\text{cm}^2$ with different weights of Nacl with different protection potentials caused by the presence of hydrogen ions in the solution, which need to draw high current to release hydrogen gas. With a protection voltage of -

1200 mV, it needs about 614 mA/cm² at 20°C and 633 μA / cm² at 30°C and at 40 it needs 773 μA/cm². Note that at a voltage of -1200 the value of the protection current is much greater than Current values for other protection voltages.

At pH = 10, at 20°C the current density varies between (25-49) μA/cm². At 30°C, the current varies between (48-87) μA/cm² and at 40°C, while for applied voltage -1200 mv, the current density from 510 μA/cm² to 644 μA/cm² at increasing temperature from 20 ° C to 40 ° C.

*** by applying SACPs method**

Figures (4-12) to (4-14) show the effect of pH on the cathodic protection current over time at different temperatures, conductivities, and different pH of the solution by applying the SACPs method. With an increase in the rate of metal dissolution, that is, the reaction rate increases with a decrease in pH. where the anode consumption is high and consumes large electrons to release hydrogen gas in this range. The dissolution of the anode due to the formation of hydroxyl ions around the structure to be protected and becomes increasingly negative in the presence of alkali and dissolved oxygen.

At pH = 7, the protection current is 36 μA/cm² at T= 20 °C increasing to 57 μA/cm² at T = 30°C and it is at T = 40°C (75 μA/cm²).

At pH = 4, the cathodic protection current increases with increasing temperature from 20 to 40°C about 36 to 232 μA/cm².

While pH=10, Since the protection current is 159 μA/cm² at 20°C and increase to 250 μA/cm² at 40°C.

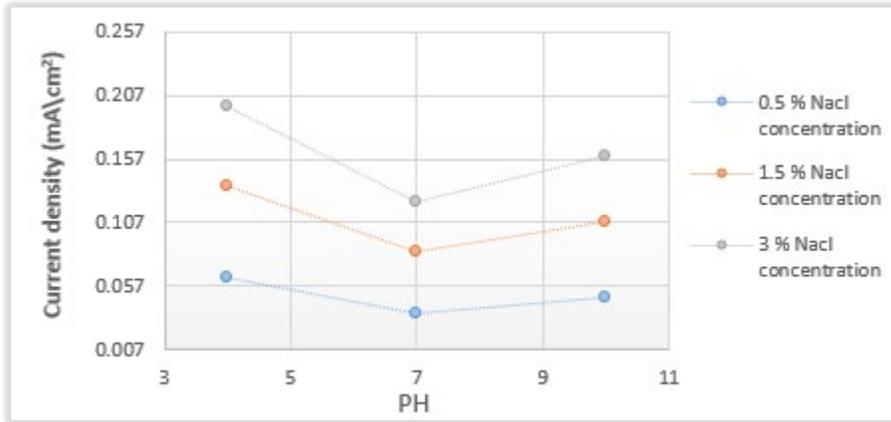


Figure (4-12): Current density vs. pH values at different Nacl concentration and T=20 °C.

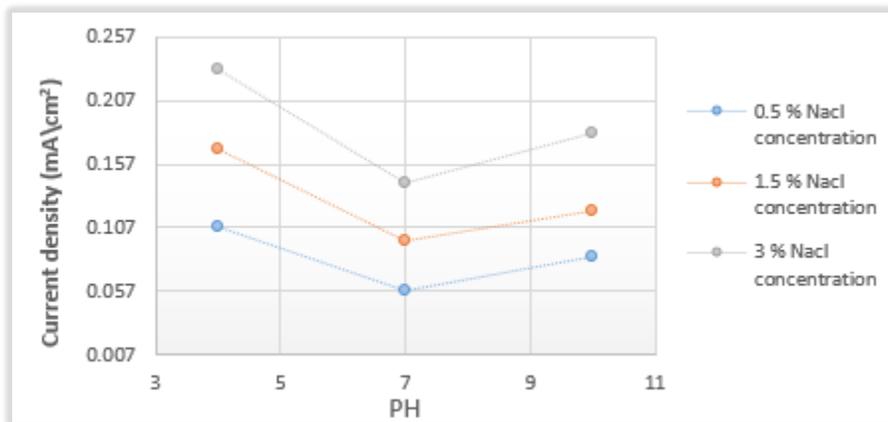


Figure (4-13): Current density vs. pH values at different Nacl concentration and T=30 °C.

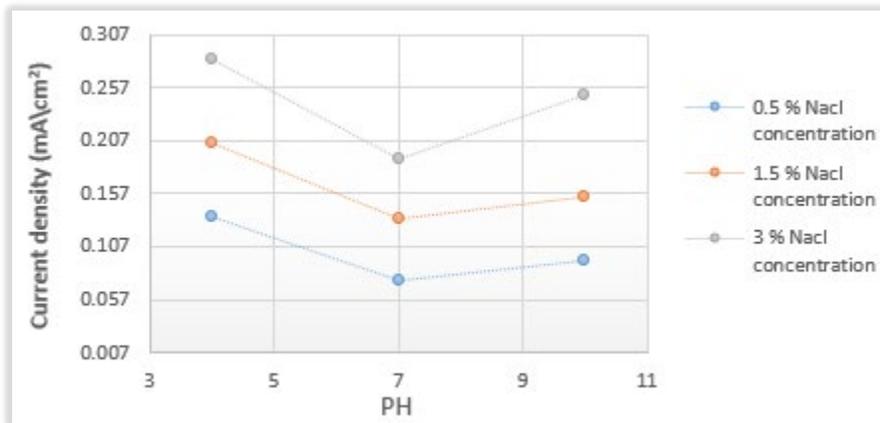


Figure (4-14): Current density vs. pH values at different Nacl concentration and T=40 °C.

The experimental data were included in the table (4-8) showing the relationship between the current density with the change of temperature, pH and concentrations.

Table (4-8): Current density vs pH values at different concentrations and a different temperature.

pH	Current density (mA/cm ²) at 0.5% NaCL			Current density (mA/cm ²) at 1.5% NaCL			Current density (mA/cm ²) at 3% NaCL		
	T=20°C	T=30°C	T=40°C	T=20°C	T=30°C	T=40°C	T=20°C	T=30°C	T=40°C
4	0.063	0.108	0.136	0.136	0.169	0.205	0.199	0.232	0.283
7	0.036	0.057	0.075	0.084	0.096	0.133	0.123	0.142	0.190
10	0.048	0.084	0.093	0.108	0.120	0.154	0.160	0.181	0.250

It is noted that the increase in concentration and temperature leads to an increase in the density of the protection current.

4.3 The Effect of Temperature on The Protection Current Density

* by applying ICCPs method

Increasing the temperature of the solution causes an increase in the mobility of the ions present in the solution and thus leads to an increase the protection current density required to protect the structure. The effect of temperature is more pronounced than that of pH. Figures (4-15) to (4-17) below show the effect of temperature on the protection current density by changing other parameters by applying ICCPs. Temperature has a major effect in the corrosion process, as the temperature rises to 40 ° C, it causes an increase in the speed of corrosion by about two or three times.

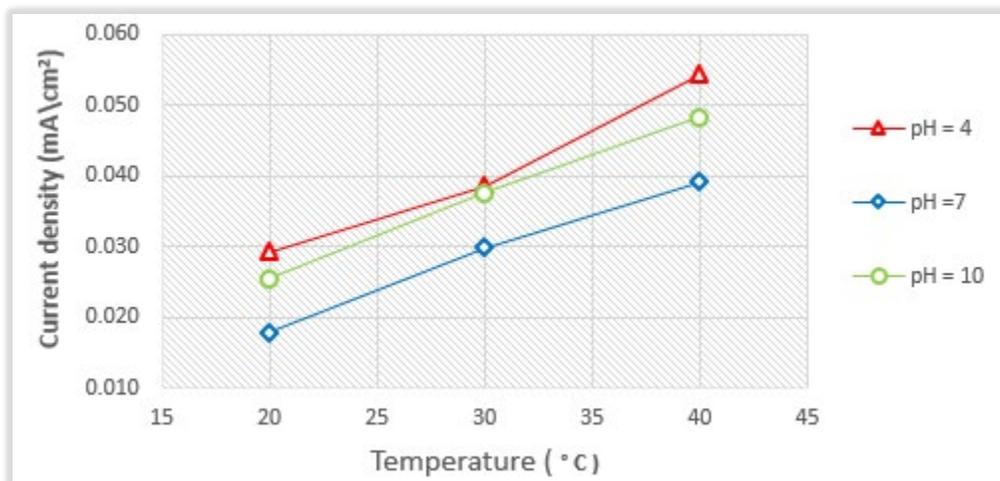


Figure (4-15): Protective Current density vs. Temperature at different pH, 0.5 NaCl concentration and -700mv.

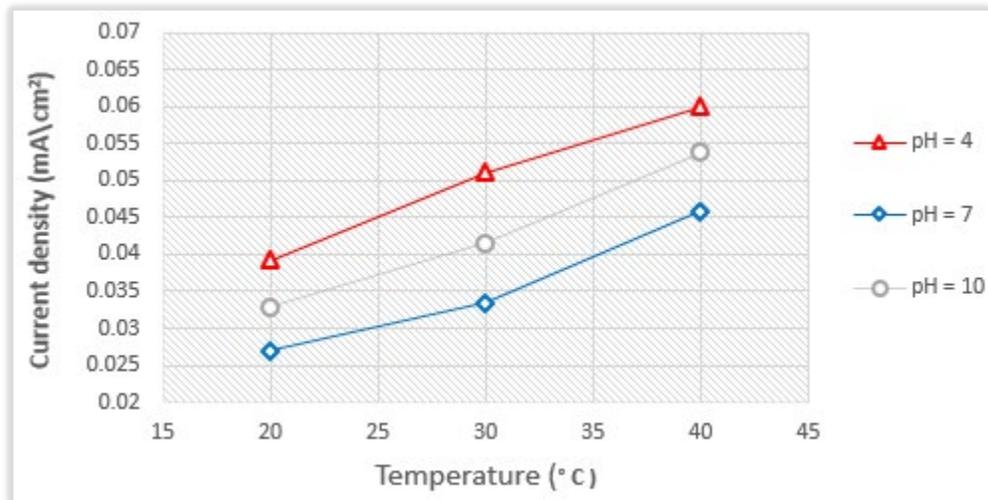


Figure (4-16): Protective Current density vs. Temperature at different pH, 1.5 NaCl concentration and -700mv.

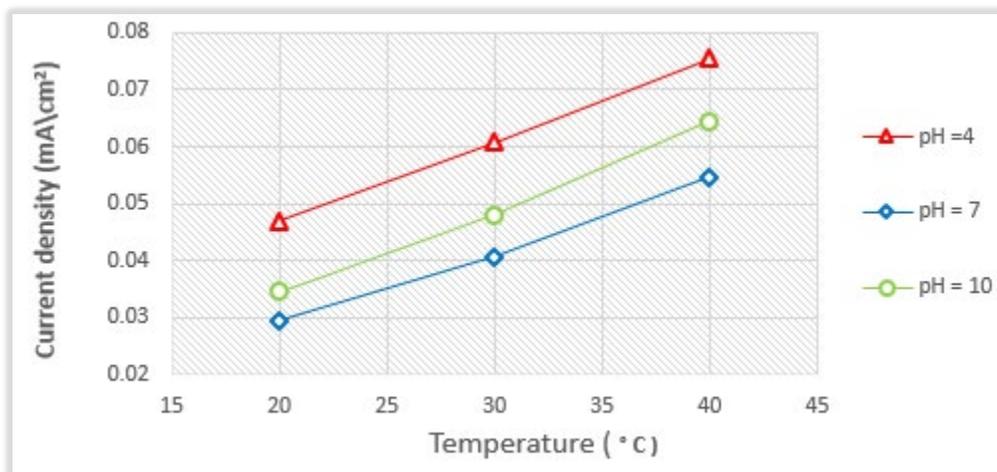


Figure (4-17): Protective Current density vs. Temperature at different pH, 3 NaCl concentration and -700mv.

At pH = 7, the current density increases with increasing temperatures from 20 to 40 ° C, ranging between (18-39) $\mu\text{A}/\text{cm}^2$, while at pH = 4 it is more than (29-54) $\mu\text{A}/\text{cm}^2$ and at pH = 10, it ranges between (25-48) $\mu\text{A}/\text{cm}^2$ in the case of voltage

Applied 700 mV and 0.5 NaCl concentration. As we increase the salt concentration, the cathodic protection increases.

Experimental results are included in a table from (4-9) to (4-11) showing the relationship between current and temperature densities at different concentrations and different pH. It is noted that the higher the concentrations with the temperature, the higher the current densities.

Table (4-9): Current density vs Temperature at different pH, different applied voltages and 0.5 NaCl concentration.

Temperature (° C)	Current density at applied voltage -700 mv (mA\cm ²)			Current density at applied voltage -900 mv (mA\cm ²)		
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10
20	0.029	0.018	0.025	0.038	0.020	0.034
30	0.039	0.030	0.038	0.049	0.034	0.038
40	0.054	0.039	0.048	0.057	0.034	0.050
Temperature (° C)	Current density at applied voltage -1000 mv (mA\cm ²)			Current density at applied voltage -1200 mv (mA\cm ²)		
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10
20	0.044	0.029	0.038	0.394	0.262	0.308
30	0.059	0.037	0.044	0.524	0.363	0.436
40	0.063	0.039	0.049	0.575	0.398	0.490

Table (4-10): Current density vs Temperature at different pH, different applied voltages and 1.5 NaCl concentration.

Temperature (° C)	Current density at applied voltage -700 mv (mA\cm ²)			Current density at applied voltage -900 mv (mA\cm ²)		
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10
20	0.039	0.027	0.033	0.049	0.031	0.042
30	0.051	0.033	0.042	0.054	0.034	0.048
40	0.060	0.046	0.054	0.066	0.049	0.057
Temperature (° C)	Current density at applied voltage -1000 mv (mA\cm ²)			Current density at applied voltage -1200 mv (mA\cm ²)		
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10
20	0.053	0.034	0.049	0.489	0.331	0.394
30	0.073	0.048	0.060	0.591	0.436	0.491
40	0.082	0.054	0.069	0.678	0.517	0.618

Table (4-11): Current density vs Temperature at different pH, different applied voltages and 3 NaCl concentration.

Temperature (° C)	Current density at applied voltage -700 mv (mA\cm ²)			Current density at applied voltage -900 mv (mA\cm ²)		
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10
20	0.047	0.029	0.035	0.053	0.036	0.046
30	0.061	0.041	0.048	0.078	0.051	0.064
40	0.075	0.055	0.064	0.093	0.061	0.079
Temperature (° C)	Current density at applied voltage -1000 mv (mA\cm ²)			Current density at applied voltage -1200 mv (mA\cm ²)		
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10
20	0.057	0.039	0.049	0.614	0.457	0.510
30	0.084	0.056	0.072	0.662	0.524	0.622
40	0.103	0.074	0.087	0.770	0.580	0.644

Figure (4-18) shows the relationship between current densities with temperatures at different applied voltages -700, -900 and -1000 mv, where the current density at the applied voltage is -1200 mv much more than other voltages.

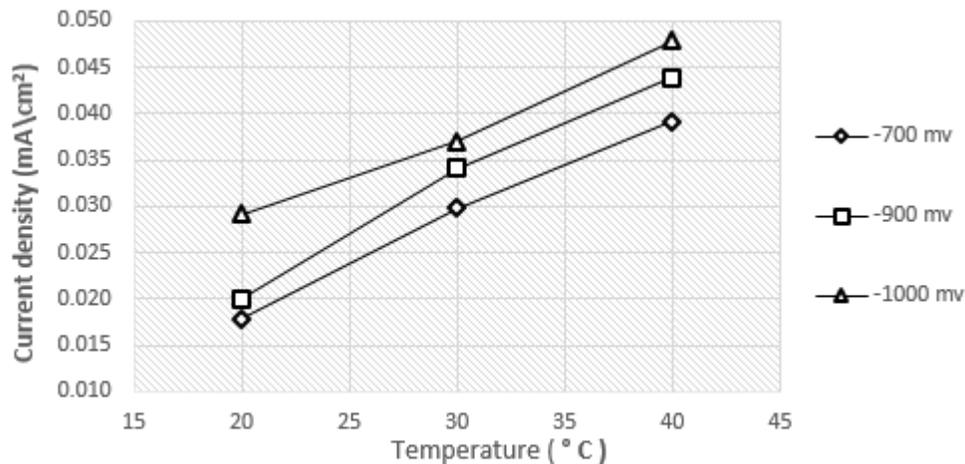


Figure (4-18): Protective Current density vs. Temperature at different applied voltages, 0.5 NaCl concentration and pH =7.

* by applying SACPs method

Figures (4-19) to (4-21) show the effect of temperature on the rate of dissolution of the metal (aluminum) over time at different conductivities, different temperatures and different pH values.

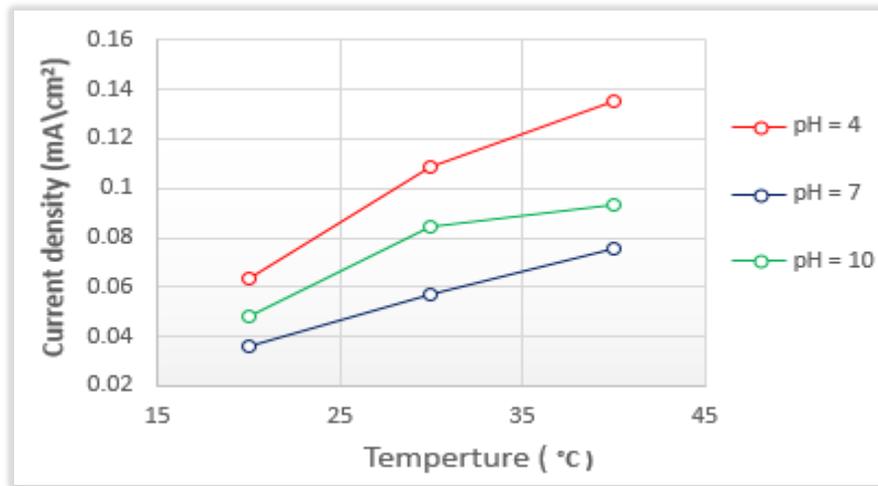


Figure (4-19): Current density vs. Temperature at different pH and 0.5 NaCl concentration

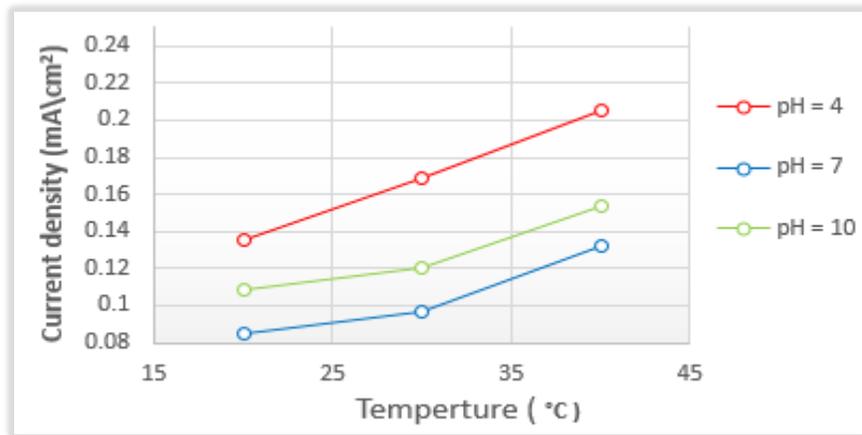


Figure (4-20): Current density vs. Temperature at different pH and 1.5 NaCl concentration

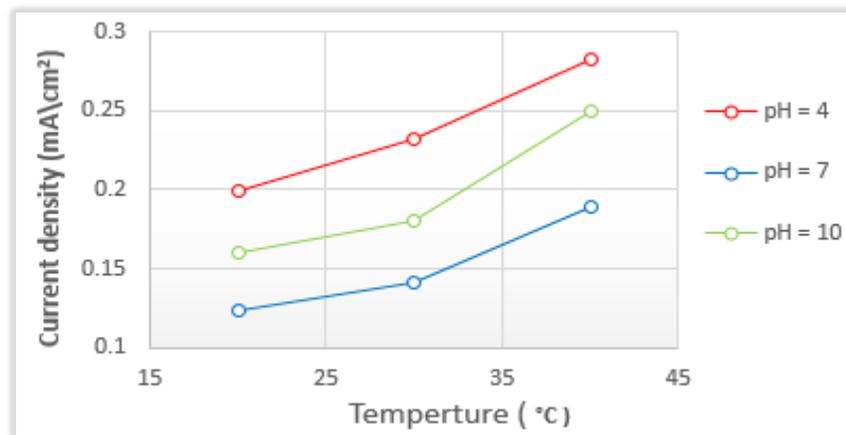


Figure (4-21): Current density vs. Temperature at different pH and 3 NaCl concentration

The higher the temperature, the higher the density of the protection current required. At pH = 7, the current densities range from (36-137) $\mu\text{A}/\text{cm}^2$ at a temperature of 20 °C, while they range from (57-142) $\mu\text{A}/\text{cm}^2$ at a temperature of 30 °C and reach 190 $\mu\text{A}/\text{cm}^2$ at a temperature of 40 °C at a concentration of 0.5 NaCl. With increasing concentration, the limits of current density increase with the difference in pH and temperature ,as shown in Table (4-12) all the experimental data for the densities of the protection current with temperatures according to the pH and concentrations.

Table (4-12): Current density vs. Temperature at different pH and different NaCl concentrations

Temperature (°C)	Current density (mA\cm ²) at 0.5% NaCL			Current density (mA\cm ²) at 1.5% NaCL			Current density (mA\cm ²) at at 3% NaCL		
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10
20	0.063	0.036	0.048	0.136	0.084	0.108	0.199	0.123	0.160
30	0.108	0.057	0.084	0.169	0.096	0.120	0.232	0.142	0.181
40	0.136	0.075	0.093	0.205	0.133	0.154	0.283	0.190	0.250

4.4 The Influence of Time on Protective Current Density

*** by applying ICCPs method**

The densities of the cathodic protection current decrease over time due to the formation of films around the structure to be protected, which increases more protection. Where the current measured at different conditions of the ICCP system at 0, 30, 60, 90, 120 min. We note that the initial protection current at all values of the protection voltages before the current source is turned on is high and when a voltage is applied and the value of the open circuit potential of the structure is determined, after 30 minutes, the protection current decreases with time for all conditions used in the work.

*** by applying SACPs method**

Figures (4-22) to (4-24) show the effect of time on the cathodic protection current density over time at different temperatures, different conductivities, and a difference in pH of the solution. It is clear that the current density decreases with time, since the rate of corrosion in the first hour decreases faster than that in the second, and this is due to the developing layer of corrosion products which grows continuously over time on the surface of the cathode (the structure to be protected) and the activity of the surface of the structure. Cathodic reactions that occur on the surface increase the pH of the environment surrounding the surface by removing hydrogen ions or by generating hydroxyl ions, all of which reduce the corrosion rate and therefore the corrosion rate of aluminum alloys decreases over time.

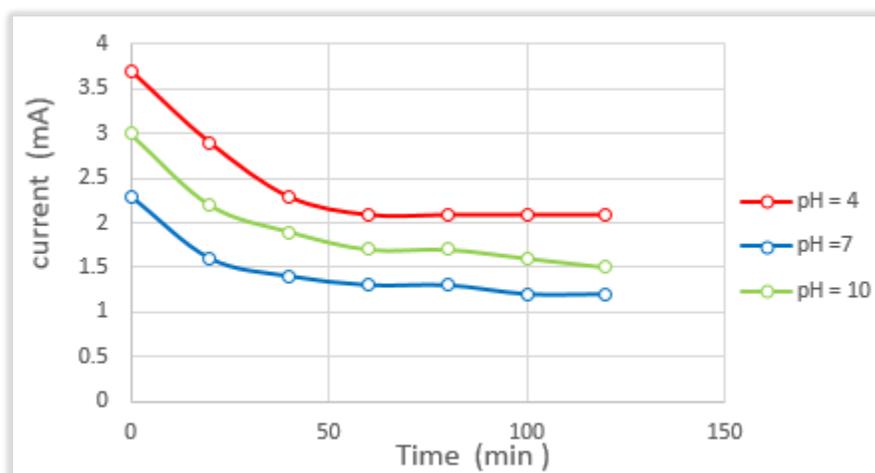


Figure (4-22): Current density vs. Time in 0.5 NaCl concentration at different pH values and $T = 20\text{ }^{\circ}\text{C}$

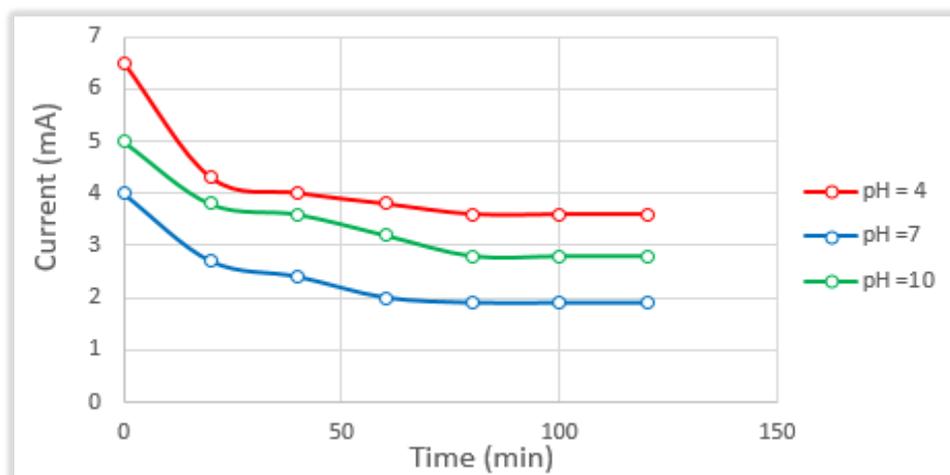


Figure (4-23) Current density vs. Time in 0.5 NaCl concentration at different pH values and $T = 30\text{ }^{\circ}\text{C}$

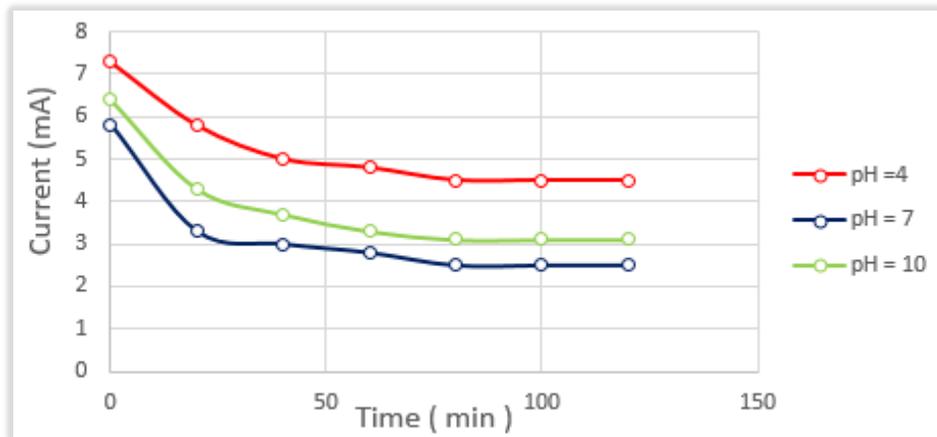


Figure (4-24): Current density vs. Time in 0.5 NaCl concentration at different pH values and $T = 40\text{ }^{\circ}\text{C}$

Similar trend is noticed by increasing the solution temperature to 30 and 40 °C and increasing the salt concentrations to 1.5 and 3% NaCl. All experimental data in Tables (4-13) to (4-15) show current densities over time under different operating conditions.

Table (4-13): Current density vs. Time at different concentrations, different pH values and $T = 20\text{ }^{\circ}\text{C}$.

Time	Current at 0.5 NaCl (mA)			Current at 1.5 NaCl (mA)			Current at 3 NaCl (mA)		
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10
0	3.7	2.3	3	6.6	4.5	5.6	9	6	6.8
20	2.9	1.6	2.2	5.3	3.4	4.2	7.7	4.8	5.7
40	2.3	1.4	1.9	5	3.2	3.9	7	4.4	5.4
60	2.1	1.3	1.7	4.8	2.9	3.7	6.8	4.2	5.4
80	2.1	1.3	1.7	4.8	2.8	3.5	6.6	4.1	5.4
100	2.1	1.2	1.6	4.8	2.8	3.5	6.6	4.1	5.4
120	2.1	1.2	1.5	4.8	2.8	3.5	6.6	4.1	5.4

Table (4-14): Current density vs. Time at different concentrations, different pH values and T= 30 °C.

Time	Current at 0.5 NaCl (mA)			Current at 1.5 NaCl (mA)			Current at 3 NaCl (mA)		
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10
0	6.5	4	5	9.5	6.1	7.7	11.2	7	8.5
20	4.3	2.7	3.8	7.3	4.9	5.5	9	5.9	6.5
40	4	2.4	3.6	6.6	4.2	5	8.5	5.2	6.3
60	3.8	2	3.2	5.7	3.7	4.7	7.8	4.9	6
80	3.6	1.9	2.8	5.6	3.5	4.4	7.7	4.7	6
100	3.6	1.9	2.8	5.6	3.2	4	7.7	4.7	6
120	3.6	1.9	2.8	5.6	3.2	4	7.7	4.7	6

Table (4-15): Current density vs. Time at different concentrations, different pH values and T = 40 °C.

Time	Current at 0.5 NaCl (mA)			Current at 1.5 NaCl (mA)			Current at 3 NaCl (mA)		
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10
0	7.3	5.8	6.4	10.2	7	8	12.1	9	12.1
20	5.8	3.3	4.3	8	5.2	6.8	9.9	7.2	9.9
40	5	3	3.7	7.7	4.7	6.2	9.7	6.6	9.7
60	4.8	2.8	3.3	7.1	4.4	5.5	9.4	6.3	9.4
80	4.5	2.5	3.1	6.8	4.4	5.1	9.4	6.3	9.4
100	4.5	2.5	3.1	6.8	4.4	5.1	9.4	6.3	9.4
120	4.5	2.5	3.1	6.8	4.4	5.1	9.4	6.3	9.4

4.5 Comparison of Sacrificial Anode and Impressed Current Cathodic Protection Methods

Figures (4-25) to (4-27) show the comparison between the two methods ICCPs and SACPs in terms of protection current density over time at different temperatures and pH values and conductivities of the solution.

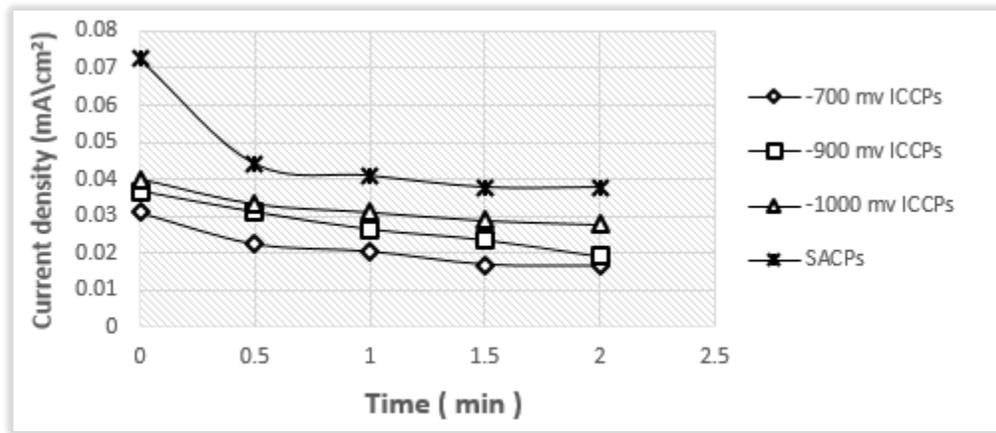


Figure (4-25): Comparison of ICCPs and SACP in 0.5 Nacl concentration at different protection voltages, a solution temperature $T=20^{\circ}\text{C}$ and pH value of 7 .

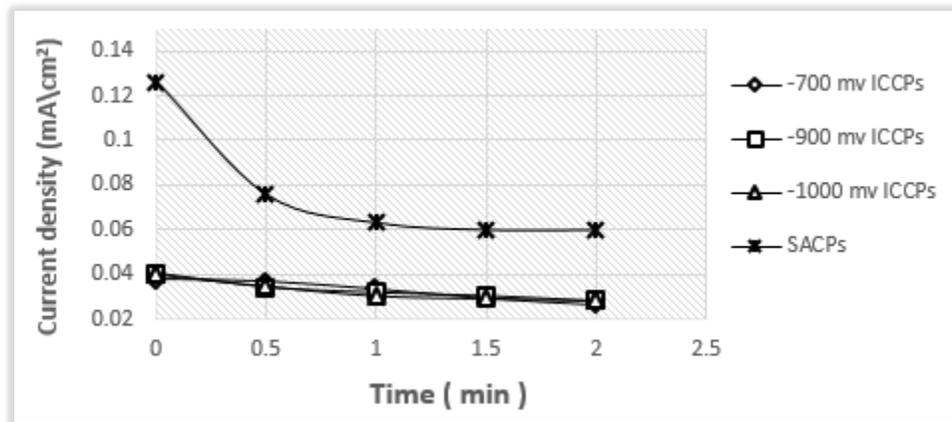


Figure (4-26): Comparison of ICCPs and SACP in 0.5 Nacl concentration at different protection voltages, a solution temperature $T=30^{\circ}\text{C}$ and pH value of 7

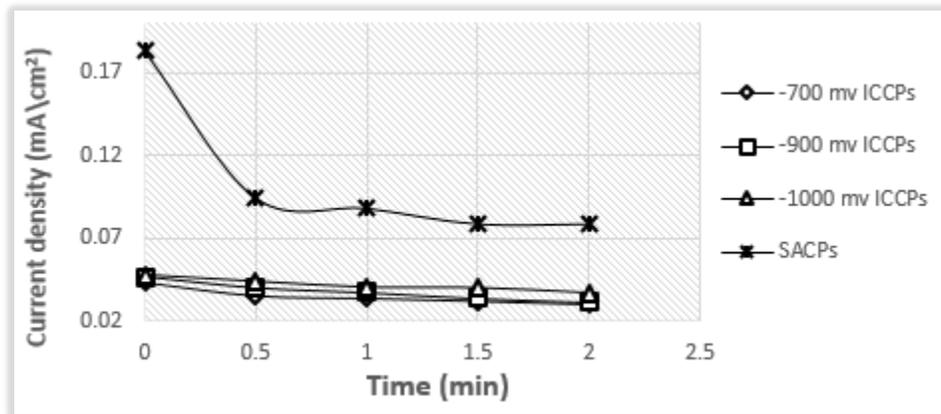


Figure (4-27): Comparison of ICCPs and SACP in 0.5 NaCl concentration at different protection voltages, a solution temperature $T=40^{\circ}\text{C}$ and pH value of 7

At $\text{pH} = 7$ and temperature 20°C , the protection current density of the ICCP system ranges between $(30\text{-}40) \mu\text{A}/\text{cm}^2$ while in the SACP system the current density is $75 \mu\text{A}/\text{cm}^2$. When the temperature increases to 40°C , the density of the protection current increases by about a range higher than $40 \mu\text{A}/\text{cm}^2$, and in a system the current is $175 \mu\text{A}/\text{cm}^2$.

Similar trends is obtained by changing the salt concentration to 1.5 and 3% and the solution temperature to 30 and 40°C and the pH values of solution to 4 and 10.

Through the above figures about the protection current for each of the ICCPs and SACP under the different operational conditions used in this research. We note that in different circumstances the cathodic protection current of the aluminum alloy is much higher than the protection current of the DC system, because in the ICCPs method it is possible to adjust the electrons that flow from a DC source to the structure to be protected and so we get a controlled protection current along the protection period.

The sacrifice method occurs as a result of the corrosion of the aluminum alloy, which is considered as a source to provide protection current to the structure and cannot be controlled as a result of the free corrosion of aluminum, so it is not possible to provide protection as we provide in the case of ICCPs. In the aluminum alloy corrosion process, pitting corrosion occurs on the surface of the alloy, which makes the aluminum alloy (anode) always active in producing electrons that protect the surface of the cathode from corrosion. It isolates it from work, so it is always used in the form of an alloy by adding elements to it. The alloy used in this work is 99% aluminum and 1% manganese, as the added manganese increases corrosion resistance significantly. In the case of using magnesium, it can give a lower corrosion rate and a better distribution of current compared to aluminum due to the high voltage of magnesium (higher than aluminum).

Tables (4-16) to (4-24) show the experimental results in different concentrations with temperatures and pH values. Over time, the current density gradually decreases, and the higher the concentrations and temperature values, the higher the cathodic protection current density, and at pH = 4 the highest protection current is needed.

Table (4-16): Comparison of ICCPs and SACPs in 0.5 NaCl concentration at different protection voltages, different pH value and a solution temperature T=20°C

Time (min)	Current density at applied voltage -700 mv (mA/cm ²)			Current density at applied voltage -900 mv (mA/cm ²)			Current density for SACPs		
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10
0	0.044	0.031	0.038	0.047	0.037	0.040	0.117	0.073	0.095
30	0.037	0.022	0.030	0.037	0.031	0.033	0.073	1.400	0.060
60	0.031	0.020	0.027	0.035	0.027	0.031	0.066	0.041	0.054
90	0.029	0.017	0.025	0.034	0.024	0.029	0.066	0.038	0.050
120	0.027	0.016	0.024	0.031	0.019	0.027	0.066	0.038	0.047
Time (min)	Current density at applied voltage -1000 mv (mA/cm ²)			Current density at applied voltage -1200 mv (mA/cm ²)					
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10			
0	0.050	0.040	0.043	0.431	0.274	0.316			
30	0.039	0.033	0.036	0.403	0.272	0.312			
60	0.036	0.031	0.034	0.397	0.269	0.307			
90	0.035	0.029	0.032	0.393	0.266	0.308			
120	0.034	0.028	0.030	0.394	0.262	0.307			

Table (4-17): Comparison of ICCPs and SACPs in 0.5 NaCl concentration at different protection voltages, different pH value and a solution temperature T=30°C

Time (min)	Current density at applied voltage -700 mv (mA/cm ²)			Current density at applied voltage -900 mv (mA/cm ²)			Current density for SACPs		
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10
0	0.058	0.038	0.050	0.062	0.040	0.050	0.205	0.126	0.158
30	0.049	0.037	0.043	0.053	0.034	0.044	0.126	0.076	0.114
60	0.046	0.033	0.042	0.051	0.032	0.040	0.114	0.060	0.088
90	0.045	0.029	0.040	0.050	0.030	0.037	0.114	0.060	0.088
120	0.043	0.027	0.036	0.048	0.028	0.035	0.114	0.060	0.088
Time (min)	Current density at applied voltage			Current density at applied voltage					

	-1000 mv (mA\cm ²)			-1200 mv (mA\cm ²)		
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10
0	0.065	0.040	0.063	0.563	0.406	0.473
30	0.058	0.035	0.044	0.546	0.401	0.467
60	0.055	0.030	0.041	0.530	0.392	0.448
90	0.052	0.029	0.041	0.528	0.370	0.441
120	0.051	0.028	0.039	0.524	0.360	0.438

Table (4-18): Comparison of ICCPs and SACPs in 0.5 NaCl concentration at different protection voltages, different pH value and a solution temperature T=40°C

Time (min)	Current density at applied voltage -700 mv (mA\cm ²)			Current density at applied voltage -900 mv (mA\cm ²)			Current density for SACPs		
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10
0	0.069	0.044	0.056	0.072	0.047	0.062	0.230	0.183	0.202
30	0.059	0.036	0.046	0.061	0.040	0.054	0.158	0.095	0.117
60	0.053	0.034	0.042	0.058	0.037	0.052	0.142	0.079	0.098
90	0.051	0.033	0.041	0.058	0.034	0.051	0.142	0.079	0.098
120	0.050	0.031	0.040	0.055	0.032	0.048	0.142	0.079	0.098
Time (min)	Current density at applied voltage -1000 mv (mA\cm ²)			Current density at applied voltage -1200 mv (mA\cm ²)					
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10			
0	0.074	0.048	0.063	0.626	0.438	0.536			
30	0.061	0.044	0.057	0.625	0.433	0.530			
60	0.059	0.040	0.055	0.593	0.402	0.498			
90	0.058	0.040	0.051	0.585	0.401	0.494			
120	0.057	0.037	0.051	0.575	0.335	0.492			

Table (4-19): Comparison of ICCPs and SACPs in 1.5 NaCl concentration at different protection voltages, different pH value and a solution temperature T=20°C

Time (min)	Current density at applied voltage -700 mv (mA/cm ²)			Current density at applied voltage -900 mv (mA/cm ²)			Current density for SACPs		
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10
0	0.047	0.034	0.039	0.061	0.044	0.055	0.208	0.142	0.177
30	0.037	0.029	0.034	0.051	0.037	0.050	0.158	0.101	0.123
60	0.036	0.026	0.032	0.051	0.034	0.047	0.151	0.088	0.110
90	0.033	0.025	0.030	0.049	0.032	0.045	0.151	0.088	0.110
120	0.031	0.025	0.029	0.048	0.030	0.045	0.151	0.088	0.110
Time (min)	Current density at applied voltage -1000 mv (mA/cm ²)			Current density at applied voltage -1200 mv (mA/cm ²)					
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10			
0	0.065	0.046	0.059	0.492	0.367	0.431			
30	0.058	0.039	0.052	0.483	0.340	0.406			
60	0.054	0.037	0.049	0.488	0.339	0.400			
90	0.054	0.035	0.049	0.489	0.335	0.396			
120	0.052	0.030	0.048	0.482	0.332	0.395			

Table (4-20): Comparison of ICCPs and SACPs in 1.5 NaCl concentration at different protection voltages, different pH value and a solution temperature T=30°C

Time (min)	Current density at applied voltage -700 mv (mA/cm ²)			Current density at applied voltage -900 mv (mA/cm ²)			Current density for SACPs		
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10
0	0.060	0.043	0.049	0.081	0.055	0.072	0.300	0.192	0.243
30	0.050	0.035	0.041	0.075	0.048	0.066	0.208	0.132	0.158
60	0.045	0.035	0.040	0.068	0.040	0.060	0.177	0.110	0.139
90	0.044	0.033	0.037	0.064	0.039	0.058	0.177	0.101	0.126
120	0.043	0.032	0.036	0.061	0.037	0.056	0.177	0.101	0.126
Time (min)	Current density at applied voltage			Current density at applied voltage					

	-1000 mv (mA\cm ²)			-1200 mv (mA\cm ²)		
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10
0	0.084	0.062	0.078	0.626	0.460	0.530
30	0.075	0.053	0.065	0.616	0.444	0.528
60	0.069	0.050	0.062	0.617	0.436	0.510
90	0.066	0.048	0.060	0.594	0.431	0.491
120	0.066	0.046	0.059	0.591	0.427	0.482

Table (4-21): Comparison of ICCPs and SACPs in 1.5 NaCl concentration at different protection voltages, different pH value and a solution temperature T=40°C

Time (min)	Current density at applied voltage -700 mv (mA\cm ²)			Current density at applied voltage -900 mv (mA\cm ²)			Current density for SACPs		
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10
0	0.077	0.056	0.066	0.094	0.061	0.081	0.322	0.221	0.252
30	0.069	0.046	0.056	0.082	0.053	0.069	0.243	0.148	0.196
60	0.059	0.043	0.052	0.079	0.049	0.065	0.215	0.139	0.161
90	0.057	0.041	0.051	0.078	0.047	0.061	0.215	0.139	0.161
120	0.055	0.040	0.049	0.077	0.047	0.060	0.215	0.139	0.161
Time (min)	Current density at applied voltage -1000 mv (mA\cm ²)			Current density at applied voltage -1200 mv (mA\cm ²)					
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10			
0	0.095	0.065	0.087	0.689	0.523	0.625			
30	0.088	0.058	0.078	0.680	0.532	0.622			
60	0.082	0.055	0.074	0.674	0.531	0.620			
90	0.082	0.054	0.073	0.667	0.525	0.618			
120	0.081	0.052	0.073	0.662	0.524	0.599			

Table (4-22): Comparison of ICCPs and SACPs in 3 NaCl concentration at different protection voltages, different pH value and a solution temperature T=20°C

Time (min)	Current density at applied voltage -700 mv (mA/cm ²)			Current density at applied voltage -900 mv (mA/cm ²)			Current density for SACPs		
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10
0	0.056	0.043	0.046	0.057	0.044	0.052	0.284	0.189	0.215
30	0.044	0.034	0.040	0.046	0.040	0.044	0.221	0.139	0.170
60	0.041	0.031	0.036	0.045	0.037	0.041	0.208	0.129	0.170
90	0.039	0.030	0.033	0.044	0.035	0.039	0.208	0.129	0.170
120	0.038	0.027	0.030	0.041	0.035	0.038	0.208	0.129	0.170
Time (min)	Current density at applied voltage -1000 mv (mA/cm ²)			Current density at applied voltage -1200 mv (mA/cm ²)					
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10			
0	0.065	0.048	0.063	0.627	0.466	0.535			
30	0.058	0.041	0.055	0.621	0.461	0.528			
60	0.058	0.041	0.051	0.611	0.459	0.518			
90	0.056	0.039	0.049	0.604	0.450	0.509			
120	0.056	0.038	0.048	0.599	0.445	0.497			

Table (4-23): Comparison of ICCPs and SACPs in 3 NaCl concentration at different protection voltages, different pH value and a solution temperature T=30°C

Time (min)	Current density at applied voltage -700 mv (mA/cm ²)			Current density at applied voltage -900 mv (mA/cm ²)			Current density for SACPs		
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10
0	0.066	0.047	0.057	0.092	0.062	0.081	0.353	0.221	0.268
30	0.056	0.046	0.049	0.081	0.049	0.073	0.268	0.164	0.199
60	0.050	0.043	0.047	0.079	0.046	0.069	0.243	0.148	0.189
90	0.048	0.041	0.045	0.078	0.045	0.065	0.243	0.148	0.189
120	0.046	0.038	0.043	0.077	0.044	0.066	0.243	0.148	0.189
Time (min)	Current density at applied voltage			Current density at applied voltage					

	-1000 mv (mA\cm ²)			-1200 mv (mA\cm ²)		
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10
0	0.095	0.057	0.087	0.682	0.554	0.653
30	0.088	0.046	0.075	0.676	0.547	0.639
60	0.086	0.044	0.074	0.674	0.526	0.660
90	0.084	0.043	0.072	0.660	0.514	0.657
120	0.083	0.042	0.070	0.656	0.507	0.654

Table (4-24): Comparison of ICCPs and SACPs in 3 NaCl concentration at different protection voltages, different pH value and a solution temperature T=40°C

Time (min)	Current density at applied voltage -700 mv (mA\cm ²)			Current density at applied voltage -900 mv (mA\cm ²)			Current density for SACPs		
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10
0	0.099	0.078	0.089	0.111	0.084	0.103	0.382	0.284	0.382
30	0.088	0.065	0.078	0.104	0.072	0.088	0.306	0.208	0.306
60	0.084	0.059	0.072	0.096	0.063	0.081	0.297	0.199	0.297
90	0.083	0.057	0.067	0.092	0.061	0.079	0.297	0.199	0.297
120	0.079	0.055	0.062	0.091	0.060	0.078	0.297	0.199	0.297
Time (min)	Current density at applied voltage -1000 mv (mA\cm ²)			Current density at applied voltage -1200 mv (mA\cm ²)					
	pH = 4	pH = 7	pH = 10	pH = 4	pH = 7	pH = 10			
0	0.114	0.085	0.106	0.792	0.617	0.684			
30	0.106	0.077	0.094	0.790	0.602	0.670			
60	0.104	0.076	0.091	0.785	0.589	0.666			
90	0.103	0.074	0.090	0.777	0.584	0.653			
120	0.101	0.073	0.089	0.773	0.579	0.645			

Chapter five

Conclusions and Recommendations for future works

5.1 Conclusions

During the experiments some points could be concluded:

- 1- The cathodic protection current density increases with increasing the salt concentration.
- 2- The effect of temperature on the cathodic protection current density is more than that of pH and salt concentration.
- 3- The cathodic protection current densities decrease with time in all the conditions studied and for ICCP and SACP systems due to the formation of a film which grows in the first hour faster than at the second hour.
- 4- The ICCP method is better and more efficient than the SACP method due to possibility of adjusting the current according to requirement.
- 5- SACPs are better than ICCPs at applied voltages -700, -900, -1000 mV, while ICCP system at -1200 mV is better than SACP system in terms of obtaining a higher cathodic protection current.

5.2 Recommendation for future works

For the future works, the following topics can be suggested to study:

- 1- It is preferable to develop a computer aided simulation model to obtain more realistic and accurate theoretical results for the two systems used in this research with the changing factors of the environment and to compare the experimental results with the theoretical results.
- 2- Different sacrificial alloys could be used like zinc and magnesium alloys.
- 3- Study the effect of fluid flow and higher range of temperatures.

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المخلص

تتعرض الهياكل المعدنية المدفونة في التربة أو الماء لأضرار جسيمة بسبب عمليات التآكل التي تسبب مشكلة هندسية واقتصادية خطيرة في جميع أنحاء العالم .

لقد حظيت هذه المشكلة باهتمام دولي واسع من خلال الكم الهائل من المؤلفات والبحوث في هذا المجال. كما جرت محاولات عديدة للتغلب عليها من خلال استخدام أنواع مختلفة من التقنيات. الأسلوب الأكثر شيوعًا وجدوى هو الحماية الكاثودية .

الحماية الكاثودية لها تطبيقات واسعة في الهياكل المختلفة، وهو تقنية كهروكيميائية فعالة لتخفيف أو منع تآكل الهياكل المعدنية .

تم استخدام عينة من الصلب الكربوني بطول 100 ملم وعرض 10 ملم وسمك 6 ملم. حوض زجاجي بأبعاد (200 x 300 x 600) ملم والمسافة بين الأقطاب ثابتة 500 ملم. تم استخدام قطب الجرافيت في نظام ICCPs وسبائك الألومنيوم في نظام الأنود المضحى (SACPs) كأقطاب موجبة. تمت دراسة العديد من المتغيرات التي تؤثر على الحماية الكاثودية للمعدن بما في ذلك تركيز كلوريد الصوديوم (0.5 ، 1.5 ، و 3) غم / لتر من الماء المقطر ، وتغيير الرقم الهيدروجيني للمحلول (4 ، 7 ، 10) ودرجات الحرارة (20 ، 30 ، 40) درجة مئوية. تم استخدام أربعة جهود للدائرة المفتوحة للمعدن (-700 ، -900 ، -1000 و -1200) ملي فولت مقابل القطب المرجعي Cu/CuSo4. تم قياس كثافة تيار الحماية الكاثودية بالإضافة إلى الجهد لمدة ساعتين. تم إجراء مقارنة بين ICCP و SACP.

تشير النتائج إلى أن SACPs أفضل من ICCPs عند جهود -700 ، -900 ، -1000 ملي فولت .



جمهورية العراق
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قسم الهندسة الكيمياءوية

بحث امكانية تطبيق الحماية الكاثودية للكربون الفولاذي في ظروف بيئية
مختلفة بطرق التيار المسلط والانود المضحى

رسالة مقدمة الى
كلية الهندسة في جامعة بابل
وهي جزء من متطلبات نيل درجة الماجستير
في الهندسة/ الهندسة الكهروكيمياوية

من قبل
فرح صالح عاصي هيكل
(بكالوريوس هندسة كهروكيمياوي 2009)

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