

Galvanic Cathodic Protection Evaluation of a Steel Pipe in Iraqi Soil

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Abstract

Corrosion is the main problem for the embedded pipelines in different environment resistivities. The most effective method to overcome this problem is cathodic protection which represents as a control method of the pipe corrosion. For achieving longer life of the external corrosion control system and evaluating the performance of aluminum alloys which have been used as sacrificed anodes to protect the embedded carbon steel pipe in different artificial simulated resistivity of soils in Iraq of [5000 , 1000 , 600 , 50 and 25 (Ω .cm)]. Results show that (Al-10 wt% Zn) as sacrificial anode alloy has the best anode capacity compared with other anodes under these conditions (Al-5 wt% Zn), and (Al-15 wt% Zn). The selection for these alloys based on that they have high potential in many environments when coupling with steels without effect of microbial, obstacle and stray current. The polarization curves of alloys also show no passivation behavior in artificial resistivities. The corrosion rate of different anode alloys was determined as a function of applied cathodic protection.

It was found a relationship between electric potential and time which determine the optimum potential in different soil types for the three above selected electrodes (anodes).

Keywords: Corrosion, Underground Corrosion, Cathodic Protection, Soil, Anode Material

تقييم منظومة الحماية الكاثودية المضحية لتربة العراقية

الخلاصة

يعتبر التآكل المشكلة الرئيسية لخطوط الانابيب المدفونة في بيئات مختلفة المقاومة . الطريقة الأكثر تأثيراً في التغلب على هذه المشكلة هي باستخدام الحماية الكاثودية والتي تمثل طريقة للسيطرة على تآكل الانابيب . في هذا البحث تم دراسة السيطرة على عمر المنظومة الخاصة بالتآكل الخاص للانابيب وتقييم للأقطاب الموجبة المصنعة لحماية الانبوب المغمور من مادة الفولاذ الكربوني في تربة مختلفة المقاومة ($5000, 1000, 600, 50, 25 \Omega$.cm). بينت النتائج ان السبيكة (Al-10 wt% Zn) المستخدمة في نظام الحماية تمتلك أفضل سعة قدرة موجبة مقارنة مع الأقطاب الموجبة الأخرى (Al – 5 wt% Zn) و (Al – 15 wt% Zn) المستخدمة في تلك الظروف. ان اختيار تلك الأقطاب الموجبة في هذا البحث لما تمتلك من جهد عالي في هكذا مقاومة و المتمثلة بمحالييل ملحية حيث تم اهمال تأثير كل من البكتريا والعوائق والتيارات الشاردة. بينت منحنيات الأستقطاب للأقطاب الموجبة عدم وجود تخميد لتلك الأقطاب في المقاوميات الأصطناعية . تم حساب معدل التآكل للأقطاب الموجبة كتطبيق للحماية السالبة المطبقة. تمت دراسة العلاقة ما بين جهد الحماية المستخدم مع الزمن ، عمر الانود ، التيار الناتج وسعة القدرة

للاقطاب المضحي بها والمستخدمة في محاليل ذات مقاومة مختلفة مع الاخذ بنظر الاعتبار المسافة ما بين القطب المحمي والقطب المضحي به.

1. Introduction

Corrosion is the deterioration of a material because of reaction with its environment [1, 2]. Corrosion of metals in soil is responsible for a large percentage of corrosion and corrosion failures. In particular, the corrosivity of soil is based largely upon the interaction of electrical resistivity, dissolved salts, moisture content, total acidity, bacterial activity, and concentration of oxygen. In addition, soil environments are generally stationary electrolyte exposure conditions [3]. For example, a review in 1995 indicates that corrosion of metals and alloys costs U.S. companies a total of approximately \$300 billion per year [4].

The corrosion of underground structures is a very widespread problem. Structures such as natural gas and crude oil pipelines and water mains are only some of the many structures reported to have been affected by soil corrosion all around the world [5].

The corrosion process in buried or partly buried structures is due to current flow from anode to cathode through the ground by ionic conductivity and from cathode to anode through the metal by electric conductivity. At the anode the metal oxidation occurs, whilst at the cathode hydrogen or oxygen reduction occurs. Anodic and cathodic areas can be closer and move along the structure surface, producing uniform corrosion, or an area can become permanently

anodic, producing localized corrosion [6].

1.2 Aim of this Work

The aim of research is to study the performance evaluation of Al-Zn

Alloy anodes in various environments (various electrical conductivities or (resistivities)) for soil in Iraq using sacrificial cathodic protection method to protect pipeline and storage tank from corrosion.

1.3 Underground Corrosion of Steel Pipes

The corrosion of underground structures is a very widespread problem. Structures such as natural gas and crude oil pipelines and water mains are only some of the many structures reported to have been affected by soil corrosion all around the world [5]. In general buried steel pipelines and tanks suffer from soil corrosion because one or more of the following conditions [7]:

1. Moisture Content in Soil.
2. pH Value
3. Soil Resistivity
4. Degree of aeration
5. Presence chlorides, sulfates microbiologically

1.4 Prevention of Underground Corrosion

The principal methods for mitigating corrosion on underground pipelines are coatings and cathodic protection. Cathodic protection accomplished by flowing a cathodic current through a metal-electrolyte interface favoring the reduction reaction over the anodic metal dissolution. This enables the entire structure to work as cathode. The two main methods are using

Sacrificial anodes or using an impressed current [2].

Cathodic protection is an electrical method of mitigating corrosion on structures that are exposed to electrolytes such as soils and waters [8].

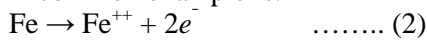
1.5 The Principle of Cathodic Protection

Metal that has been extracted from its primary ore (metal oxides or other free radicals) has a natural tendency to revert to that state under the action of oxygen and water. This action is called corrosion and the most common example is the rusting of steel.

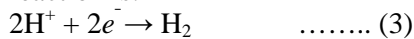
Corrosion is an electro-chemical process that involves the passage of electrical currents on a micro or macro scale. The change from the metallic to the combined form occurs by an “anodic” reaction:



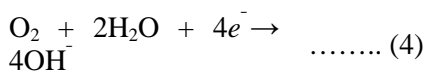
A common example is:



This reaction produces free electrons, which pass within the metal to another site on the metal surface (the cathode), where it is consumed by the cathodic reaction. In acid solutions the cathodic reaction is:



In neutral solutions the cathodic reaction involves the consumption of oxygen dissolved in the solution:



The principle of cathodic protection is in connecting an external anode to the metal to be protected and the passing of an

electrical dc current so that all areas of the metal surface become cathodic and therefore do not corrode. The external anode may be a galvanic anode, where the current is a result of the potential difference between the two metals, or it may be an impressed current anode, where the current is impressed from an external dc power source. In electro-chemical terms, the electrical potential between the metal and the electrolyte solution with which it is in contact is made more negative, by the supply of negative charged electrons, to a value at which the corroding (anodic) reactions are stifled and only cathodic reactions can take place [9, 10].

1.6 Types of Cathodic Protection:

There are two types of Cathodic Protection Systems [11].

1. Sacrificial or galvanic cathodic protection system which used of metals which are more reactive than the metal to be protected from corrosion.

2. Impressed current cathodic protection system which used of a direct current power source and auxiliary anodes

1.6.1 Sacrificial Anode Cathodic Protection

Sacrificial anode type cathodic protection systems provide cathodic current by galvanic corrosion. The current is generated by metallicity connecting the structure to be protected to a metal/alloy that is electrochemically more active than the material to be protected. (Both the structure and the anode must be in contact with the electrolyte). Current discharges from the expendable anode, to the electrolyte, and onto the structure to be protected, as shown in Figure 1. [8].

The materials used for sacrificial anodes are either relatively pure active metals such as zinc or magnesium, or alloys magnesium or aluminum that have been specifically developed for use as sacrificial anodes. In applications where the anodes are buried, a specie chemical backfill material surrounds the anode in order to insure that the anode will produce the desired output [12].

2. Experimental Work

The experimental work deals with a system of cathodic protection which has been designed and assembled.

1. Preparation of electrode specimens (sacrificial anodes and bare pipe to be protected) which have been used in cathodic protection by sacrificial anode method.
2. Preparation of electrolyte (solution equivalents to value of resistivity for soil in Iraq).
3. Electrochemical evaluation of the anodes.

2.1 Fabrication of the anodes

The anode electrodes were manufactured by die casting from Aluminum alloys. An electric furnace (Carbolite) was used to cast Aluminum - Zinc alloys. Anodes have been prepared by casting in the required wt% Zn in a graphite crucible, kept in a muffle furnace, at 750 +/- 30 °C. The melt was stirred using a silicon carbide rod. The homogeneous melt was poured into a preheated stainless steel die of (108.5×68.5×98.5) mm³ dimensions, and diameter (17) mm. Then the specimens were left to cool to room temperature. Sacrificial anode electrodes made from (Al – 5 wt% Zn), (Al – 10 wt% Zn) and (Al – 15

wt% Zn). Chemical analysis of these specimens was shown in Table 1.

2.2 Cathode Electrode

Tubes of low carbon steel used as bare pipe to be protected with specifications of (2.7) cm outside diameter and (2.4) cm inside diameter and (12) cm length. The chemical composition of these specimens is shown in Table 2.

2.3 Preparation of Solution

The solution was prepared experimentally (Solution equivalents to resistivities for soil in Iraq) in different concentrations of (0.01 %, 0.05%, 0.1%, 1% & 3%) NaCl, by adding different weights of (0.1, 0.5, 1, 10 & 30 g) sodium chloride (NaCl) to 1 liter of tap water as shown in Table 3.

The solution resistivities (5000, 1000, 600, 50, 25 Ω.cm) which represented moderate to severe condition of large extent of land in north Iraq – Turkey pipeline in Nineva to Um–Qaser in Basrah. This condition was considerate without effect of bacteria and any other obstacles.

2.4 Electrochemical Evaluation of the Anodes.

2.4.1 Polarization

The sacrificial anodes were anodically polarized potentiostatically. A saturated calomel electrode was the reference electrode. The polarization experiments were repeated for testing the reproducibility. The anodes were equilibrated in the 3.5% NaCl solution for sufficient time prior to each polarization.

2.4.2 Sacrificial Cathodic Protection system

The test anode and a suitable cathode of low carbon steel (pipe) was coupled together and immersed

in different of NaCl solutions (0.01 %, 0.05%, 0.1%, 1% & 3%) and the distances between them ranges between (40 and 60) cm for a period of 2 hour. A saturated calomel electrode was the reference electrode placed in the center media of pipe. Recording the potential with time after 2 minutes for 2 hr and current output for sacrificial by digital Aovometer. The weight of the anode before and after the immersion of the galvanic couple for a period of 2 hours was measured after cleaning and drying the anode.

2.5 Determine Life and Capacity of Anode

The anode capacity of a galvanic anode is calculated using the equation. [13];

$$A_c = \left(\frac{A_L \times I \times 8760}{A_w \times U_F} \right) \dots\dots (5)$$

Where:

- A_c = Anode capacity (A.hr/Kg)
- A_L = Anode Life (year), A_L = mass of sacrificial anode/ consumption rate
- Consumption rate = weight loss / time (kg/hr)
- I = Discharged current (Amper)
- A_w = Anode Weight (Kg)
- U_F = Utilization factor = 0.9
- 8760 = Total hours in a year

2.6 Calculation of Corrosion Rate of sacrificial anodes

The corrosion rates for sacrificial anodes alloys (Al – 5 wt% Zn), (Al – 10 wt% Zn) and (Al – 15 wt% Zn) were calculated after potentiostat test as given below [1]:-

$$C.R. (gmd) = 1.117 \times I_{corr} \times (n / wt) \quad (6)$$

where:

- C.R. : corrosion rate (gmd)
- wt: atomic weight (g/mole)
- I_{corr} : corrosion current (μA)
- n : common valance.

3. Results and Discussion

3.1 Potential Protection

3.1.1 Cathodic Protection at Concentration 0.01% NaCl

From Figures (2), (3) and (4) which represent the relationship between potential and time. The potential protection for steel pipe when using calomel electrode was (-800 mV) [14], the potential protection for the three mentioned figures seems to be more than (-800 mV). Therefore these three selected sacrificial anodes did not protect the steel pipe due to their potential where were more than the desired value. In this stage the type of anode alloys that didn't protect the pipe were determined.

3.1.2 Cathodic Protection at Concentration 0.05% NaCl

Figures (5), (6) and (7) represent the relationship between potential and time. The potential protection for steel pipe when using calomel electrode was (-800 mV), the potential protection from the three mentioned figures seems to be more than (-800 mV) because the higher resistivity for solution (low electrical conductivity) between sacrificial anode and pipe to be protected. Therefore these three selected sacrificial anodes did not protect the steel pipe due to their potentials which are more than the desired value.

3.1.3 Cathodic Protection at Concentration 0.1% NaCl

From Figures (8), (9) and (10) represent the relationship between potential and time. The potential protection for steel pipe when using calomel electrode was (-800 mV), the potential protections from the three mentioned figures, are more than (-800 mV) because the higher

resistivity for solution (low electrical conductivity between sacrificial anode and pipe to be protected). Therefore these three selected sacrificial anodes did not protect the steel pipe due to their potentials which are more than the desired value.

3.1.4 Cathodic Protection at Concentration 1% NaCl

Figures (11), (12) and (13) show that all alloys can protect steel pipe because its potential here is less than that potential of pipe protection due to electrical conductivity between sacrificial anode and pipe to be protected. Except alloy (Al-5wt%Zn) with distance of 60 cm where it did not supply protection because its potential was (-704 mV).

3.1.5 Cathodic Protection at Concentration 3% NaCl

Figures (14), (15) and (16) show higher potential is less than of steel potential which was (-800 mV). Therefore they introduce good protection to steel pipe due to electrical conductivity between sacrificial anode and pipe to be protected.

3.2 Anode Life and Anode Capacity

Cathodic protection anodes have specific parameters relating to their rates of consumption and utilization. These determine the useful life that can be obtained from an anode operating at or below its calculated current output [13]. Table 4. shows the anode life and anode capacity for all sacrificial anode alloys.

Anode life is primarily governed by weight, current output, and efficiency. The heavier anode gives longer life, the higher current the shorter life, the higher efficiency the longer life.

Table 5. show the above optimization depends also on fixing the resistivity because each resistivity value represents a simulated separated region.

Therefore the work optimization divided into five separate parts as follows:

a – Region of resistivity of 25 Ω .cm

The best selected anode was with the alloy of Al-10 wt%Zn and 60 cm far away from structure. This gives anode life of 5.7 years with anode capacity of 2482 A.hr/kg. Elfitouri K. et al [15], have found that the anode capacities (for Al-4.5wt%Zn with trace amounts of In and heat treatments i.e. one of them was annealed and the other was water quenched) are 2305 A.hr/kg, and 2294 A.hr/kg respectively. Comparing with our value of 2482 A.hr/kg. It is clear that it is not far away from their results.

b - Region of resistivity of 50 Ω .cm

The best selected anode was with conditions of alloy Al-10 wt%Zn and 60 cm far from the structure which gives anode life of 7.6 years with anode capacity of 3407 A.hr/kg.

c- Region of resistivity of 600, 1000 and 5000 Ω .cm Ω .cm

All conditions were not suitable because the potential was more than -800 mV (negative value) leads to corrode the structure instead of sacrificing aluminum anodes.

It can be noticed from all the above optimizations that the best selection the anode capacity was the higher value for each resistivity group.

In this work, the Al-10 wt%Zn alloy is the best one from the three selected alloys.

3.2 Potentiostat Test

Figures (17) to (19) illustrate the corrosion behavior of sacrificial anode alloys polarized in 3.5% NaCl solutions. All polarization curves show cathodic and anodic regions. Table 6. show the corrosion rate of sacrificial anodes. An alloy (Al – 10 wt% Zn) is of low corrosion rate as compared with (Al – 5 wt% Zn) and (Al – 15 wt% Zn). Because the formation layer of Al_2O_3 is built up slows down the corrosion of Zn in the alloy.

Figures (20) to (22) show the microstructure of (Al – 5 wt% Zn), (Al – 10 wt% Zn) and (Al – 15 wt% Zn) respectively after immersion test (potentiostat). When testing the selected anode electrode by potentiostat test, it seems that the Al – 10 wt% Zn has less corrosion rate than the others.

Under anodic polarization the local composition variation will favor the initiation and propagation of macro- and micro local phenomena's (i.e. galvanic corrosion or pitting). These phenomena are responsible for lowering the anode efficiency either by electrochemical or mechanical mass loss (grain or particles drop). The zinc corrosion rate was slow due to alumina layer (Al_2O_3) formation on the surface of the alloy. While in the alloy (Al – 15 wt% Zn) the corrosion rate was higher due to cracking of the formed alumina layer.

Finally, the alloy (Al – 10 wt% Zn) was chosen as sacrificed electrode in sacrificial cathodic protection system due to long life and low corrosion operation to the steel pipes therefore it was chosen as the best specified electrode from the selected sample or alloys.

4. Conclusion

This study introduces a new method to determine the performance of selected aluminum anodes [(Al – 5 wt% Zn), (Al – 10 wt% Zn) (Al – 15 wt% Zn)] which were used in galvanic anode. Following conclusions can be drawn:

1. The anode current is able to reach a proper distance from the anode center and meet the requirements for cathodic protection with this region.
2. Cathodic protection is actually achieved by a counter electromotive force that forces cathodic protection reactions to occur at the protected surface. Current is not the cause of corrosion but an effect of the corrosion process.
3. The potential increases in the negative direction when increasing time to approach fix potential, in region 25 and 50, $\Omega.cm$ the potential is a provide protection to steel pipe because the potential is less than – 800 mV, while the regions 600, 1000 and 5000 $\Omega.cm$ the potential does not provide protection to steel pipe because the potential is more than – 800 mV.
4. The parameters solution resistivity, distance between cathode and anode, and different alloys (sacrificial anodes) and their interactions have significant effect on the cathodic protection current.
5. In All ranges of resistivity 25 – 5000 $\Omega.cm$, the best selected sacrificial anode is the alloy (Al -10 wt% Zn) because it gives higher capacity and life with protection potential less than -800 mV to protect steel pipe as compared with other alloys.
6. Current density output from the sacrificial anodes in sacrificial cathodic protection system decreases

with increasing the distance between sacrificial anode and protected pipe from 40 to 60 cm, and increases with decreasing the solutions resistivity from 5000 for 25 Ω .cm. The current density value best anode (Al-10wt%Zn) alloy are (45.37 and 46.71 $\mu\text{A}/\text{cm}^2$) for 25 and 50 Ω .cm respectively as compared with current density of alloy (Al-10%Mg-5.5%Zn) with value (12.36 $\mu\text{A}/\text{cm}^2$) alloy which used as sacrificial anode to protect oil pipelines that pass through Al-FAO region in Southern Iraq [16]. The anode spacing has to be established to obtain a suitable current distribution over the entire pipe.

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**Table (1) The practical chemical composition
of Al – Zn alloys used in wt%**

Sample	Zn %	Fe %	Cu %	Pb %	Al %
Al-5%Zn	4.5	0.545	0.004	0.017	Balance
Al-10%Zn	9.5	0.477	0.006	0.469	Balance
Al-15%Zn	14	0.692	0.015	1.881	Balance

Table (2) The chemical composition of the tubes in wt%.

C %	Si %	Mn %	S %	P %	Fe %
≤ 0.17	0.03 0.3	– 0.2 0.5	– 0.04	0.08	balance

Table (3) The characteristic of the solutions.

Concentration NaCl %	NaCl content g/l	Conductivity μΩ/cm	Resistivity Ω.cm
0.01	0.1	200	5000
0.05	0.5	1000	1000
0.1	1	1666.66	600
1	10	20000	50
3	30	40000	25

**Table (4) Represent alloy type, distance, resistivity, life, current and capacity
At anode mass of 0.05 kg with U_f equal 0.9.**

Alloy type	Distance cm	Resistivity $\Omega.cm$	Anode life hr	Anode life year	Current A	Potential -mV	Anode capacity A.hr/Kg
Al - 5%Zn	40	25	33333	3.8	0.002237	977	1657.037
Al - 10%Zn	40	25	41667	4.8	0.002267	984	2099.074
Al - 15%Zn	40	25	45455	5.2	0.002138	956	2159.596
Al - 5%Zn	60	25	38462	4.4	0.0022	982	1880.342
Al - 10%Zn	60	25	50000	5.7	0.002234	990	2482.222
Al - 15%Zn	60	25	45455	5.2	0.00199	941	2010.101
Al - 5%Zn	40	50	32258	3.7	0.0024	864	1720.43
Al - 10%Zn	40	50	50000	5.7	0.00252	860	2800
Al - 15%Zn	40	50	47619	5.4	0.00201	869	2126.984
Al - 5%Zn	60	50	40000	4.6	0.002162	704	1921.778
Al - 10%Zn	60	50	66667	7.6	0.0023	913	3407.407
Al - 15%Zn	60	50	45455	5.2	0.001957	898	1976.768
Al - 5%Zn	40	600	55556	6.3	0.001307	780	1613.58
Al - 10%Zn	40	600	90909	10	0.001305	795	2636.364
Al - 15%Zn	40	600	83333	9.5	0.001171	806	2168.519
Al - 5%Zn	60	600	62500	7.1	0.001153	757	1601.389
Al - 10%Zn	60	600	100000	11	0.001196	763	2657.778
Al - 15%Zn	60	600	90909	10	0.001156	745	2335.354
Al - 5%Zn	40	1000	90909	10	0.000689	676	1391.919
Al - 10%Zn	40	1000	111111	13	0.000857	690	2116.049
Al - 15%Zn	40	1000	100000	11	0.000694	620	1542.222
Al - 5%Zn	60	1000	142857	16	0.000674	692	2139.683
Al - 10%Zn	60	1000	111111	13	0.000784	710	1935.802
Al - 15%Zn	60	1000	111111	13	0.000688	678	1698.765

Al - 5%Zn	40	5000	83333	9.5	0.000671	649	1242.593
Al - 10%Zn	40	5000	125000	14	0.000835	650	2319.444
Al - 15%Zn	40	5000	142857	16	0.000672	682	2133.333
Al - 5%Zn	60	5000	90909	10	0.000662	649	1337.374
Al - 10%Zn	60	5000	142857	16	0.000667	643	2117.46
Al - 15%Zn	60	5000	166667	19	0.000658	643	2437.037

Table (5) The best of Selection Sacrificial Anode

Solution resistivity $\Omega.cm$	Sacrificial Anode type	Distance between Sacrificial Anode & protect pipe	Anode life (year)	Potential protection (-mV)	Anode capacity (A.hr/Kg)
25	Al-10wt%Zn	60 cm	5.7	990	2482
50	Al-10wt%Zn	60 cm	7.6	913	3407
600	-	-	-	-	-
1000	-	-	-	-	-
5000	-	-	-	-	-

Table (6) The corrosion rate of sacrificial anodes.

Sample	E_{corr} mV	i_{corr} $\mu A/cm^2$	Surface Area cm^2	I_{corr} μA	Corrosion Rate gmd
Al – 5 % Zn	- 1000.4	1.01	0.785	0.793	0.095
Al – 10 % Zn	- 968.1	0.619	0.785	0.485	0.056
Al – 15 % Zn	- 956.6	11.18	0.785	8.776	0.993

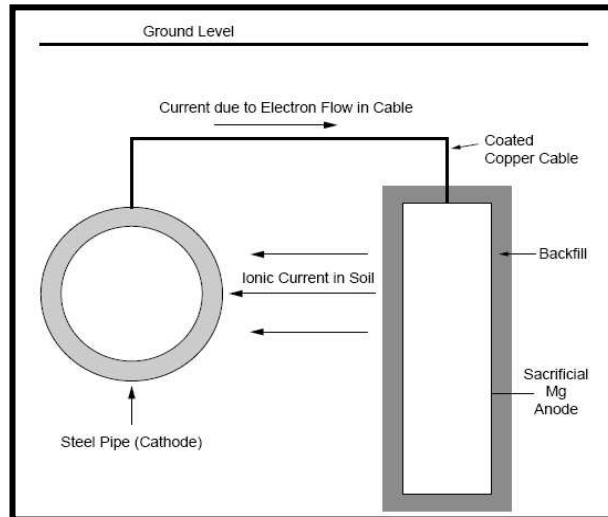


Figure (1) Principle of cathodic protection with sacrificial anodes [8].

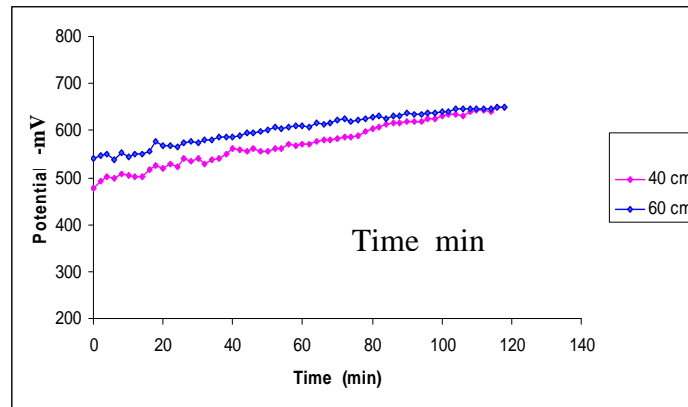


Figure (2) Potential vs. Time for sacrificial cathodic Protection

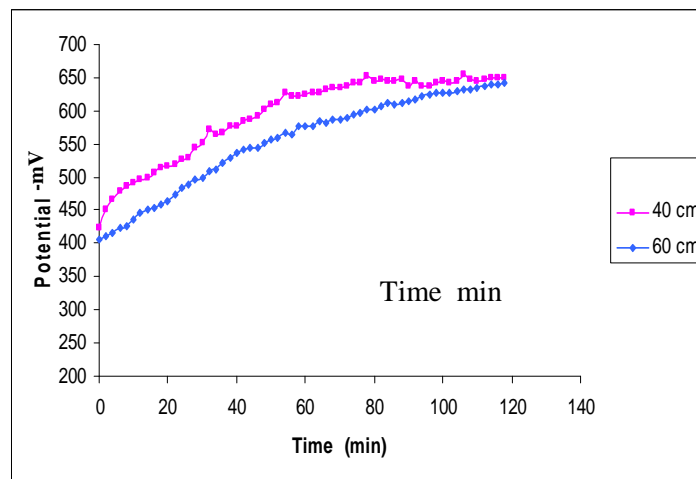


Figure (3) Potential vs. Time for sacrificial cathodic protection system to (Al - 10wt%Zn) in 0.01% NaCl at 25 °C

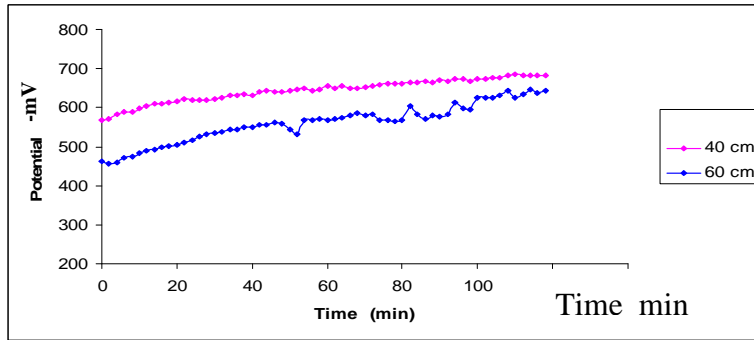


Figure (4) Potential vs. Time for sacrificial cathodic protection system to (Al – 15wt%Zn) in 0.01% NaCl at 25 °C

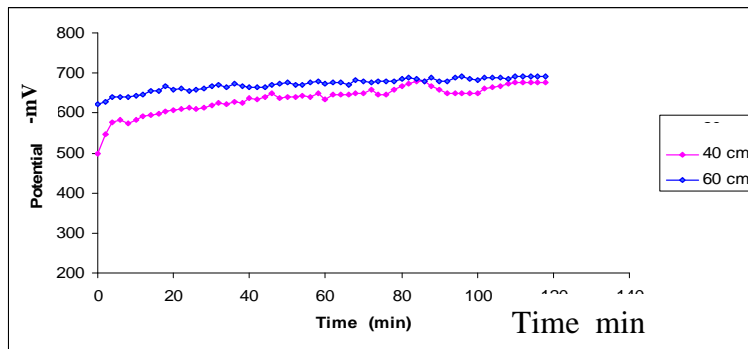


Figure (5) Potential vs. Time for sacrificial cathodic protection system to (Al – 5wt%Zn) in 0.05% NaCl at 25 °C

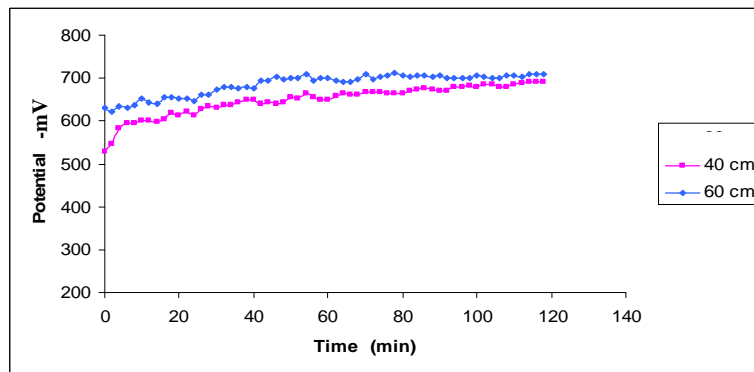


Figure 6. Potential vs. Time for sacrificial cathodic protection system to (Al – 10wt%Zn) in 0.05% NaCl at 25 °C

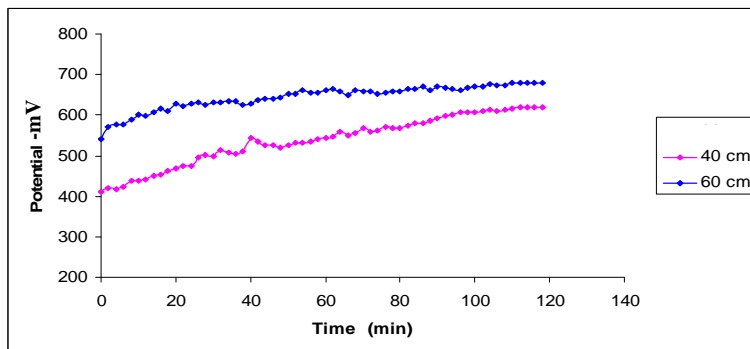


Figure (7) Potential vs. Time for sacrificial cathodic protection system to (Al – 15wt%Zn) in 0.05% NaCl at 25 °C

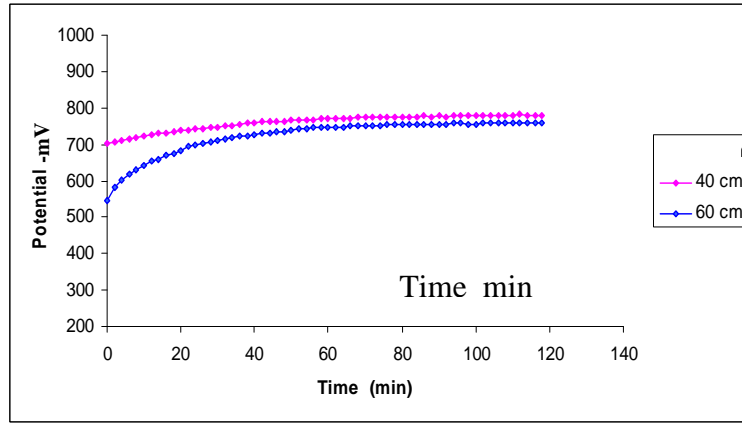


Figure (8) Potential vs. Time for sacrificial cathodic protection system to (Al – 5wt%Zn) in 0.1% NaCl at 25 °C

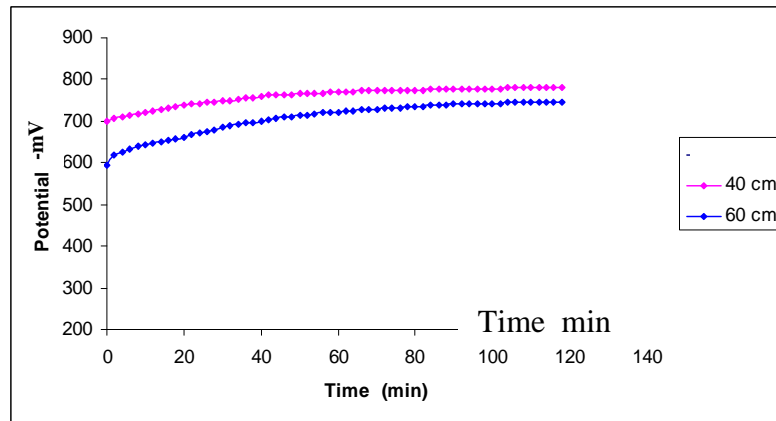


Figure (9) vs. Time for sacrificial cathodic protection system to (Al – 10wt%Zn) in 0.1% NaCl at 25 °C

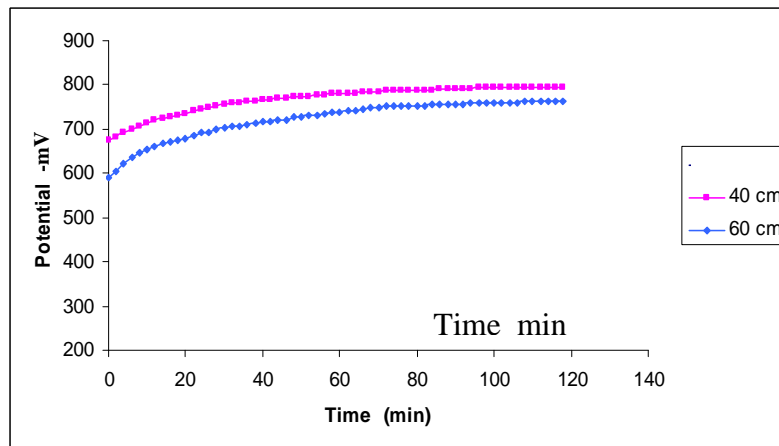


Figure (10) Potential vs. Time for sacrificial cathodic protection system to (Al – 15wt%Zn) in 0.1% NaCl at 25 °C

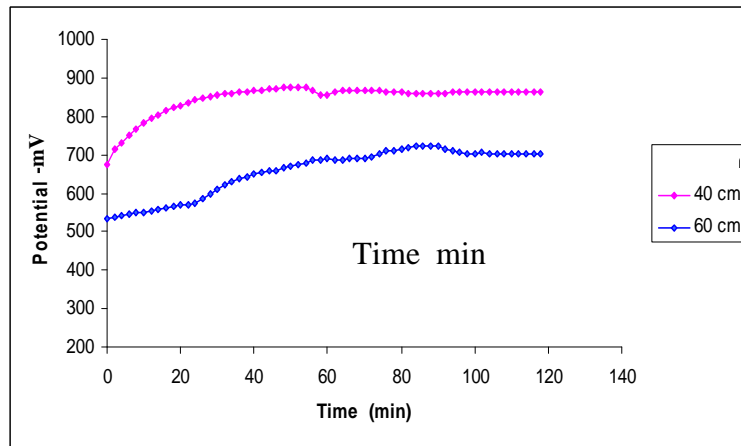


Figure (11) Potential vs. Time for sacrificial cathodic protection system to (Al – 5wt%Zn) in 1% NaCl at 25 °C

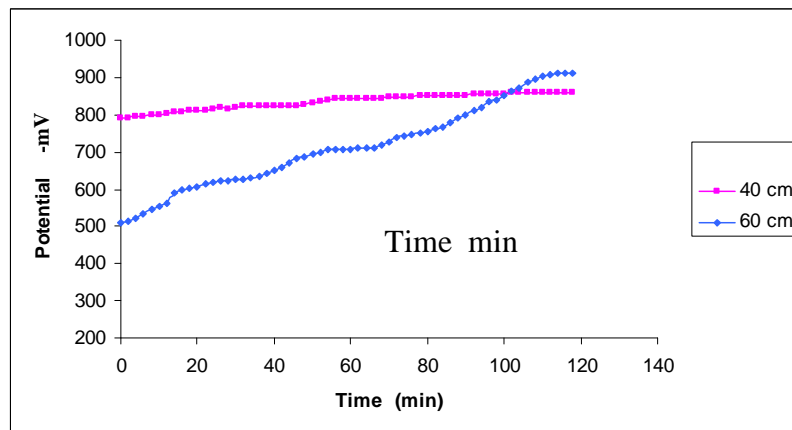


Figure (12) Potential vs. Time for sacrificial cathodic protection system to (Al – 10wt%Zn) in 1% NaCl at 25 °C

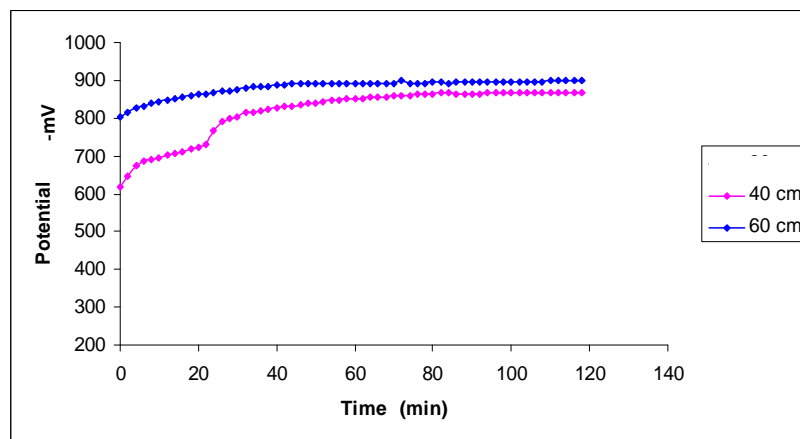


Figure 13. Potential vs. Time for sacrificial cathodic protection system to (Al – 15wt%Zn) in 1% NaCl at 25 °C

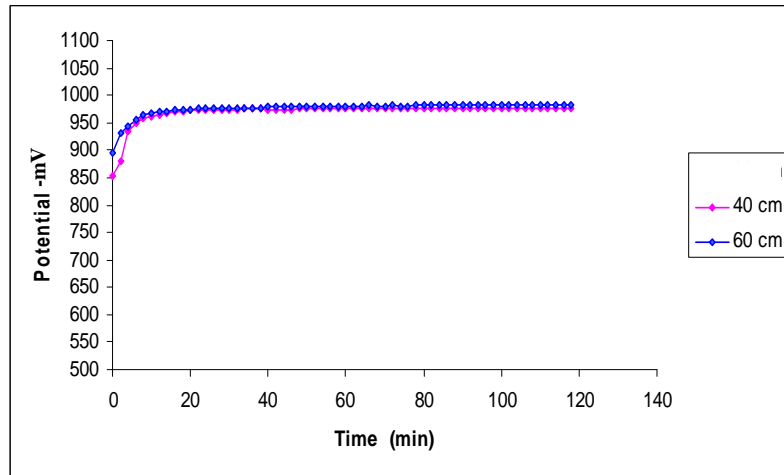


Figure (14) Potential vs. Time for sacrificial cathodic protection system to (Al - 5wt%Zn) in 3% NaCl at 25 °C

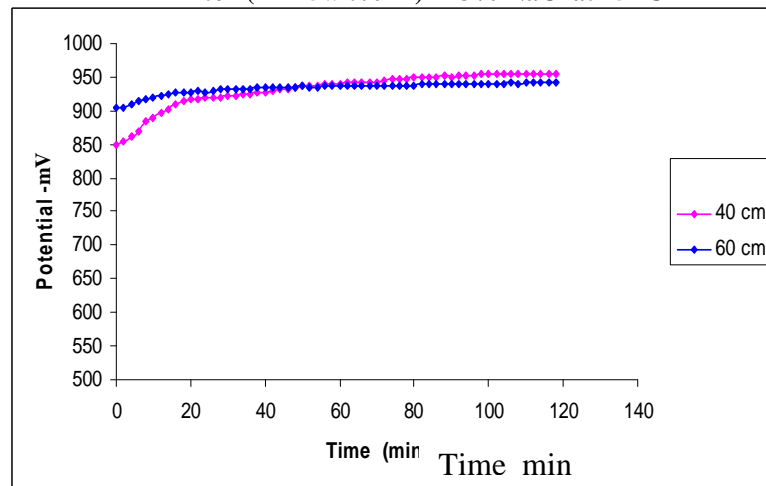


Figure (15) Potential vs. Time for sacrificial cathodic protection system to (Al - 15wt%Zn) in 3% NaCl at 25 °C

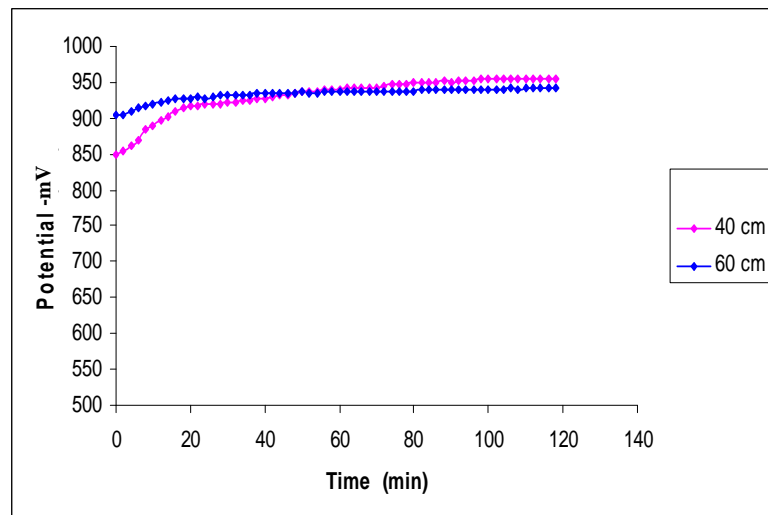


Figure 16. Potential vs. Time for sacrificial cathodic protection system to (Al - 15wt%Zn) in 3% NaCl at 25 °C

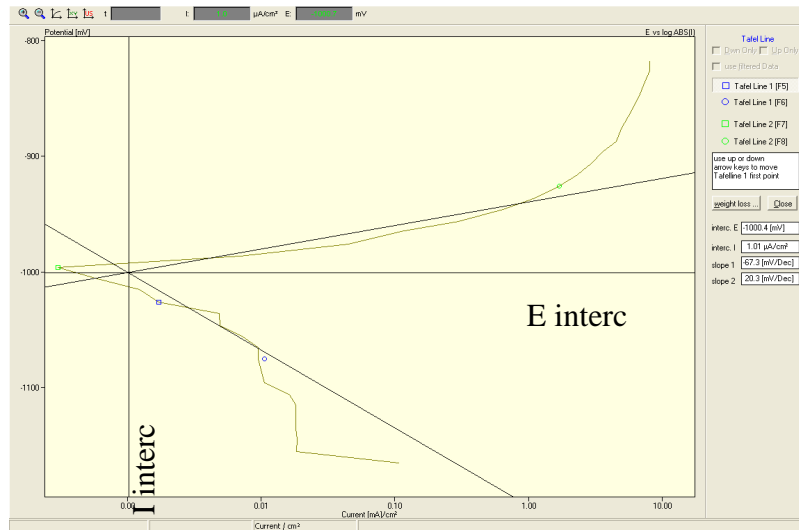


Figure (17) Potentiostat test for Al – 5wt% Zn

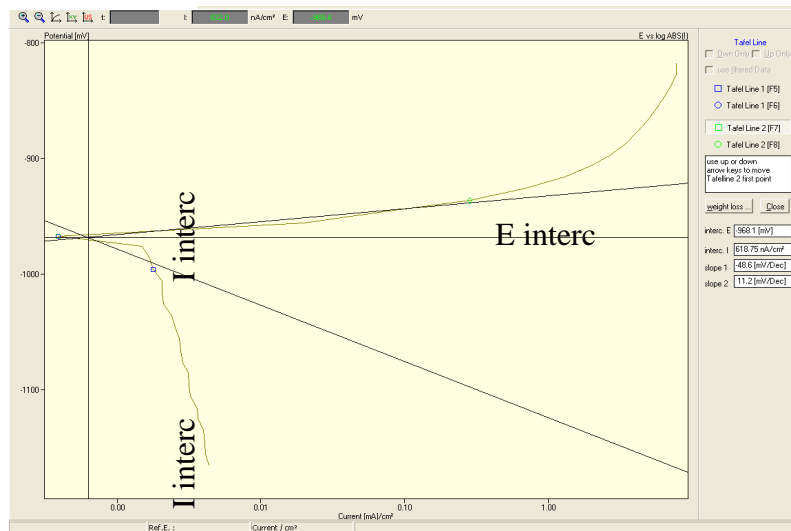


Figure (18) Potentiostat test for Al – 10wt% Zn

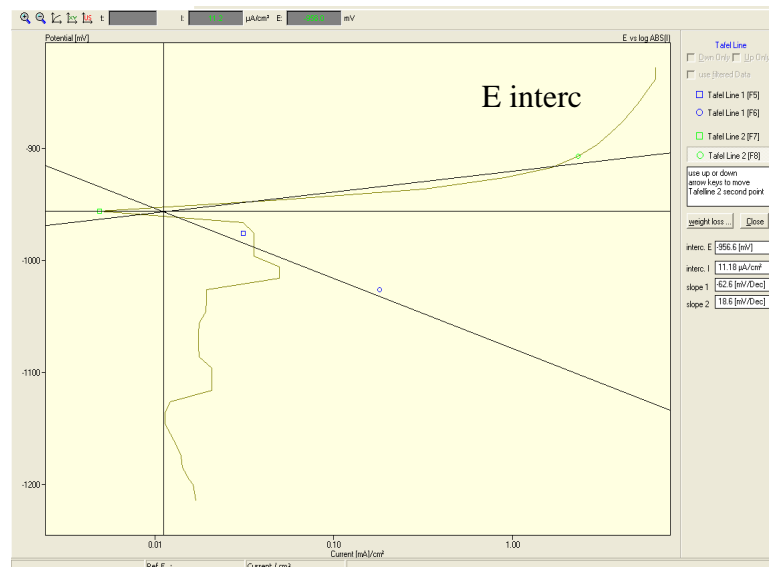


Figure (19) Potentiostat test for Al – 15wt% Zn



Figure 20. show the microstructure of Al – 5wt% Zn alloy after immersion, X 100

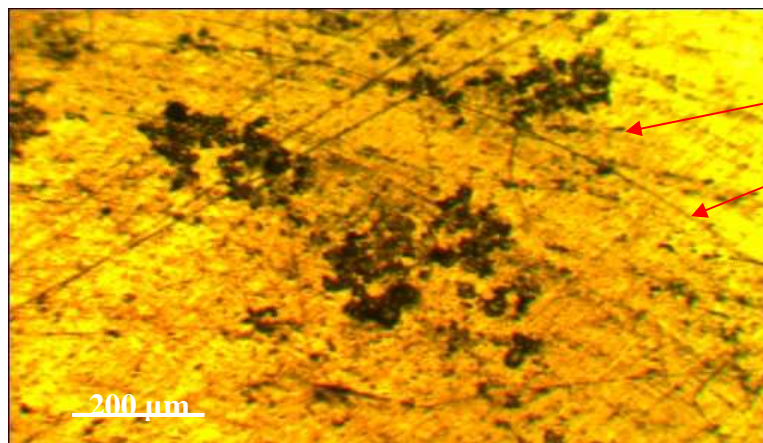


Figure 21. show the microstructure of Al – 10wt% Zn alloy after immersion, X 100

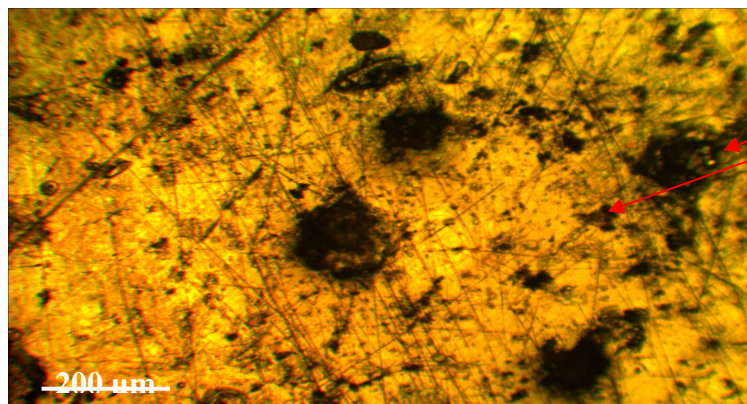


Figure 22. show the microstructure of Al – 15wt% Zn alloy after immersion, X 100