DEVELOPMENT OF ELECTRICAL RESISTANCE BASED CORROSION RATE SENSOR

By

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Dissertation report
Submitted in partial fulfillment of the requirements for the
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(Electrical & Electronics Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Electrical & Electronics Engineering Programme
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Approved:

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December 2009

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Mohd Zulhilmi Bin Mat

ABSTRACT

This report describes the work done on investigating the change of electrical resistance of copper wires in a corroding solution. The work was carried out as part of a project to develop a miniaturized electrical resistance based corrosion rate sensor. This work will be carried out by using three different thicknesses of copper wires. The experimental measurement will be done to investigate the change in electrical resistance of each wire in corrosive agent. The corrosive agent used is 3.5% salinity of water which is typically used in corrosion study. For the literature review, description of corrosion itself will be introduced first. This is followed by a brief description of Electrical Resistance(ER) technique to monitor corrosion. At the end of this report, some findings and data collection out of this work are discussed. Finally, the conclusion of the work done is included together with some recommendations for future work.

ACKNOWLEDGEMENTS

All praise to Allah the Almighty, who has helped and gave me the courage and strength to complete the project dissertation of Final Year Project. With His Grace and Mercy, this endeavour is now a success.

I would like to take this opportunity to express my deepest gratitude to all parties involved in conducting this project, ranging from Universiti Teknologi PETRONAS lecturers, technicians, graduate assistants to external establishments who have put in a large effort in turning this project into a reality.

I am profoundly grateful to my supervisor, Dr Zainal Arif Burhanudin, who has guided and given me this once in a lifetime opportunity to handle this project. Compliments also goes to all Electrical and Electronics Engineering lecturers and technicians for being ever helpful in providing assistance and giving constructive criticisms to help improve the project.

I would like to dedicate this project to family and friends for giving their tireless support and continuous motivation throughout this last one year in completing this project.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

In processing plant, liquid and gaseous can be kept at a specific pressure using pressure vessels. To supply these materials to the pressure vessels, thermally insulated carbon-steel pipe are typically used. Often, however, the pipelines corrode, under the thermal insulator and later leaks undetected.

Metallic corrosion is the destructive attack of a metal as it is exposed to an environment. It is an electrochemical process and usually starts of the surface. It involves the transfer of electrons from one chemical species to the other one. Characteristically the neutral metal atoms loose electron. This process is called oxidation reaction [1].

There are lots of methods in detecting the corrosion and one of it is electrical resistance (ER) method. It operates by measuring the change in electrical resistance of a metallic element immersed in a product media relative to a reference element sealed within the probe body. Since temperature changes effect the resistance of both the exposed and protected element equally, measuring the resistance ratio minimizes the influence of changes in the ambient temperature. Therefore, any net change in the resistance ratio is solely attributable to metal loss from the exposed element once temperature equilibrium is established. If the corrosion occur in the vessel under study is roughly uniform, a change in resistance is proportional to an increment of corrosion.

1.2 Problem Statement

Big & bully, corrosion monitoring by using Electrical Resistance(ER) technique is difficult to integrate on an Integrated Circuit(IC). So the solution for that problem is by miniaturizing it. The work was carried out as part of a project to develop a miniaturized electrical resistance based corrosion rate sensor. The corrosion rate sensor is important to detect and monitor the corrosion. For example, corrosion of a pipe can cause small spots of weakness, which if not detected and fixed, could result in a pipe catastrophe. Subsidence of the soil, local construction projects, seismic activity, weather, and simply wear and tear from the friction of fluids passing through a pipeline can lead to defects and anomalies in the pipeline.

The serious consequences of the corrosion process have become a problem of worldwide significance. In addition to our everyday encounters with this form of degradation, corrosion causes plant shutdowns, waste of valuable resources, loss or contamination of product, reduction in efficiency, costly maintenance, and expensive overdesign.. Corrosion control is achieved by recognizing and understanding corrosion mechanisms, by using corrosion resistant materials and designs, and by using protective systems, devices, and treatments.. Such a situation can easily breed negligence and be quite costly in terms of dollars and human lives [2].

Significant of the Project:

This project is benefit to the process plant industry in term of safety, cost, time and quality. However, Electrical Resistance(ER) technique is not only to monitor corrosion at processing plant, but it also can be used in automation industry, shipping industry and other industry that prompt to corrosion. By monitoring the condition of the metal used in the industry, corrosion can be detected and right action can be taken immediately.

1.3 Objective and Scope of Study

The objectives of this project are:

1) To investigate the change in electrical resistance of corroding wires with and without corrosive agent. .
2) To obtain corrosion rate of the wires within corrosive agent.

Scopes of study are:

1) Software simulation using Athena and Atlas.

   The purpose is to validate the theory that relates to the thickness of material with electrical resistance. This is done by obtaining the IV characteristic from the simulation.

2) Experimental measurement of change in electrical resistance of Copper wires in corrosive solution.

CHAPTER 2
LITERATURE REVIEW

2.1 Definition of Corrosion

Corrosion means the disintegration of a material into its constituent atoms due to chemical reactions with its surroundings. In the most common use of the word, this means a loss of electrons of metals reacting with water and oxygen. Weakening of iron due to oxidation of the iron atoms is a well-known example of electrochemical corrosion. This is commonly known as rusting. This type of damage typically produces oxide(s) and/or salt(s) of the original metal. Corrosion can also refer to other materials than metals, such as ceramics or polymers. Although in this context, the term degradation is more common.

Most structural alloys corrode merely from exposure to moisture in the air, but the process can be strongly affected by exposure to certain substances. Corrosion can be concentrated locally to form a pit or crack, or it can extend across a wide area to produce general deterioration. While some efforts to reduce corrosion merely redirect the damage into less visible, less predictable forms, controlled corrosion treatments such as passivation and chromate-conversion will increase a material's corrosion resistance [3].

2.1.1 *Rate of Corrosion*

The corrosion rate, of the rate of material removal as a consequence reaction, can be expressed as the Corrosion Penetration Rate, or the thickness loss of material per unit time. The formula of the Corrosion Penetration Rate (CPR) is as per below:

$$CPR = \frac{K.W}{\rho AT}$$

K is a constant, its magnitude depending on the system of unit used

K= 87.6 for mm/year; K= 534 for mils per year (mpy)

W= Length loss after exposure time,t,(mg)

ρ = density of material (g/ cm^3); t = exposure time (hours)

2.2 Resistivity of Wires

The electrical resistance of a wire would be expected to be greater for a longer wire, less for a wire of larger cross sectional area, and would be expected to depend upon the material out of which the wire is made. Experimentally, the dependence upon these properties is a straightforward one for a wide range of conditions, and the resistance of a wire can be expressed as

$$R = \frac{\rho L}{A}$$

ρ = resistivity
L = length
A = cross sectional area

The factor in the resistance which takes into account the nature of the material is the resistivity. Although it is temperature dependent, it can be used at a given temperature to calculate the resistance of a wire of given geometry [4]. Table 1 below shows the resistivity of difference wires and temperature coefficient at 20 C.

Table 1 : Resistivity of Wires

Material	Resistivity (ohm m)		Temperature coefficient per degree C	Conductivity x 10^7 /□m
Silver	1.59	x10^{-8}	.0061	6.29
Copper	1.68	x10^{-8}	.0068	5.95
Aluminum	2.65	x10^{-8}	.00429	3.77
Tungsten	5.6	x10^{-8}	.0045	1.79
Iron	9.71	x10^{-8}	.00651	1.03
Platinum	10.6	x10^{-8}	.003927	0.943
Manganin	48.2	x10^{-8}	.000002	0.207
Lead	22	x10^{-8}	...	0.45
Mercury	98	x10^{-8}	.0009	0.10
Nichrome (Ni,Fe,Cr alloy)	100	x10^{-8}	.0004	0.10
Constantan	49	x10^{-8}	...	0.20
Carbon* (graphite)	3-60	x10^{-5}	-.0005	...
Germanium*	1-500	x10^{-3}	-.05	...
Silicon*	0.1-60	...	-.07	...
Glass	1-10000	x10^{9}	...	...
Quartz (fused)	7.5	x10^{17}	...	...
Hard rubber	1-100	x10^{13}	...	...

The resistivity of semiconductors depends strongly on the presence of impurities in the material, a fact which makes them useful in solid state electronics.

2.3 Salinity of Water

In order to implement the investigation of electrical resistance in corrosive solution, it is important to identify what types of solution that is used as corrosive agent. The objective is to make the salinity of corroding solution same with salinity of salinity of seawater, that is 3.5%. On average, seawater in the world's oceans has a salinity of about 3.5%. This means that every 1 kilogram (2.2 lb) of seawater has approximately 35 grams (1.2 oz) of dissolved salts (mostly, but not entirely, the ions of sodium chloride: Na^+, Cl^-. Seawater is denser than freshwater (which reaches a maximum density of 1.000 g/ml at a temperature of 4 °C (39 °F) because of the salts’ added mass. The freezing point of sea water decreases with increasing salinity and is about −2 °C (28.4 °F) at 35 g/l [5].

2.3.1 Salinity

Although the vast majority of seawater has a salinity of between 3.1% and 3.8%, seawater is not uniformly saline throughout the world. Where mixing occurs with fresh water runoff from river mouths or near melting glaciers, seawater can be substantially less saline.

2.3.2 Water Salinity

- the average salinity of ocean water is 35 parts per 1000 parts of salt water
- in deeper ocean waters the salinity is about 35 parts per 1000

2.4 Electrical Resistance Monitoring System

The electrical resistance (ER) technique is an online method of monitoring the rate of corrosion and the extent of total metal loss for any metallic equipment or structure. The ER technique measures the effects of both the electrochemical and the mechanical components of corrosion such as erosion or cavitation. It is the only online, instrumented technique applicable to virtually all types of corrosive environments.

Although universally applicable, the ER method is uniquely suited to corrosive environments having either poor or non-continuous electrolytes such as vapors, gases, soils, "wet" hydro-carbons, and nonaqueous liquids. Examples of situations where the ER approach is useful are:

- Oil/gas production and transmission systems
- Refinery/petrochemical process streams
- External surfaces of buried pipelines
- Feedwater systems
- Flue gas stacks
- Architectural structures

An ER monitoring system consists of an instrument connected to a probe. The instrument may be permanently installed to provide continuous information, or may be portable to gather periodic data from a number of locations. The probe is equipped with a sensing element having a composition similar to that of the process equipment of interest [6].

2.4.1 *Resistance Relationship with Reduced Radius*

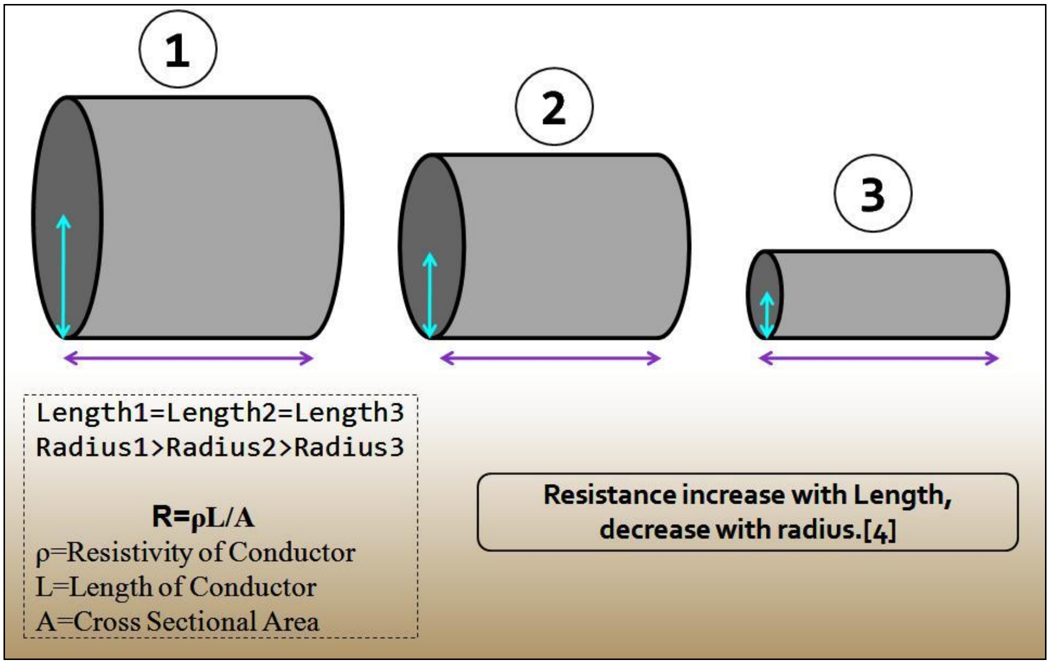

Figure 1 : Resistance Relationship with Reduced Radius

Figure 1 shows solid conductor with three different radii, Radius1, Radius2, and Radius3 and have same length, resistivity, voltage supplied and made of the same material. The thicker one, Conductor 1 has largest cross sectional area while Conductor 3 has smallest cross sectional area (A).

The average speed of the electrons will be the same in all 3 different conductors with different radii. However, we must think of electrons moving across the cross sectional area of each conductor. This means there will be more electrons, in total, passing across conductor with Radius1 than conductors with Radius2 and Radius3. There is a higher current in the thicker conductor. A higher current for a given voltage means a lower resistance. Conductor 1 has a lower resistance than conductor 2 and conductor 3. The electrical resistance increase with decreasing thickness. The resistance of a solid conductor depends on the length, the diameter (cross sectional area, A) of the conductor, and its resistivity. Resistance increases with length, decreases with area [10].

2.4.2 Principles of ER Operation

Reduction (metal loss) in the element's cross section due to corrosion will be accompanied by a proportionate increase in the element's electrical resistance.

Measurement is carried out using ER probes equipped with an element that is freely exposed to the corrosive fluid, and a reference element sealed within the probe body. Measurement of the resistance ratio of the exposed to protected element is made as shown in Figure 2.

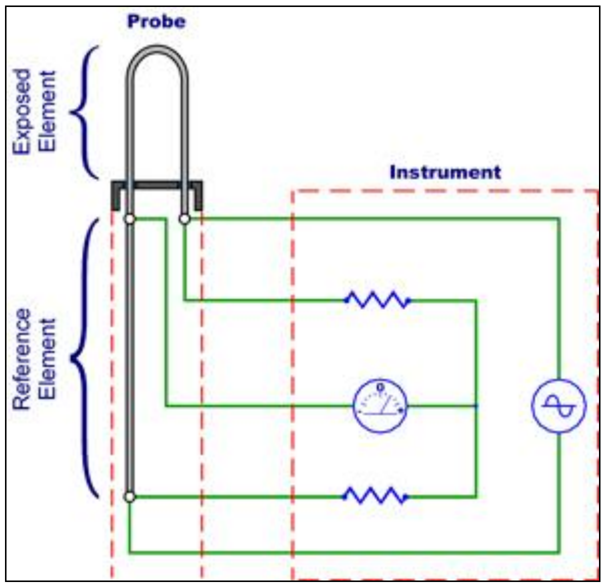

Figure 2 : ER Probe/Instrument

Since temperature changes effect the resistance of both the exposed and protected element equally, measuring the resistance ratio minimizes the influence of changes in the ambient temperature. Therefore, any net change in the resistance ratio is solely attributable to metal loss from the exposed element once temperature equilibrium is established.

All standard metal samples corrosion monitoring systems ER probes incorporate a third element called the check element. Because the check element is also sealed within the probe body, the ratio of its resistance to that of the reference element should remain unchanged. Any significant change in this ratio indicates a loss of probe integrity.

Measurement of the ER probe may either be taken periodically using a portable instrument, or on a continuous basis using a permanently installed unit.

In either case, corrosion monitoring systems ER instruments will produce a linearized signal which is proportional to the metal loss of the exposed element. The rate of change in the instrument output is a measure of the corrosion rate. Continuously monitored data is usually transmitted to a computer/data-logger and treated to give direct corrosion rate information [8]. Manual graphing techniques are usually used to derive corrosion rate from periodically obtained data as illustrated in Figure 3.

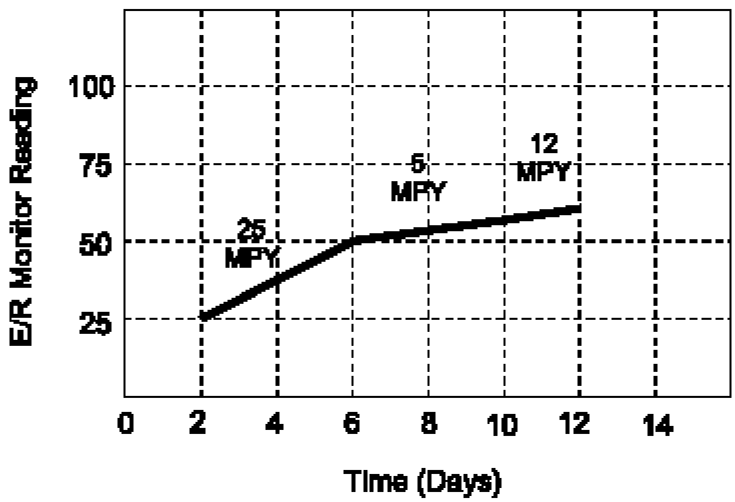

Figure 3 : Graph ER Monitor Reading versus Time

2.4.3 ER Sensing Elements

This part of literature review will describe about the sensing elements that are used to sense and monitor corrosion of material. Sensing elements are available in a variety of geometric configurations, thicknesses, and alloy materials. Available element types are shown in Figure 4.

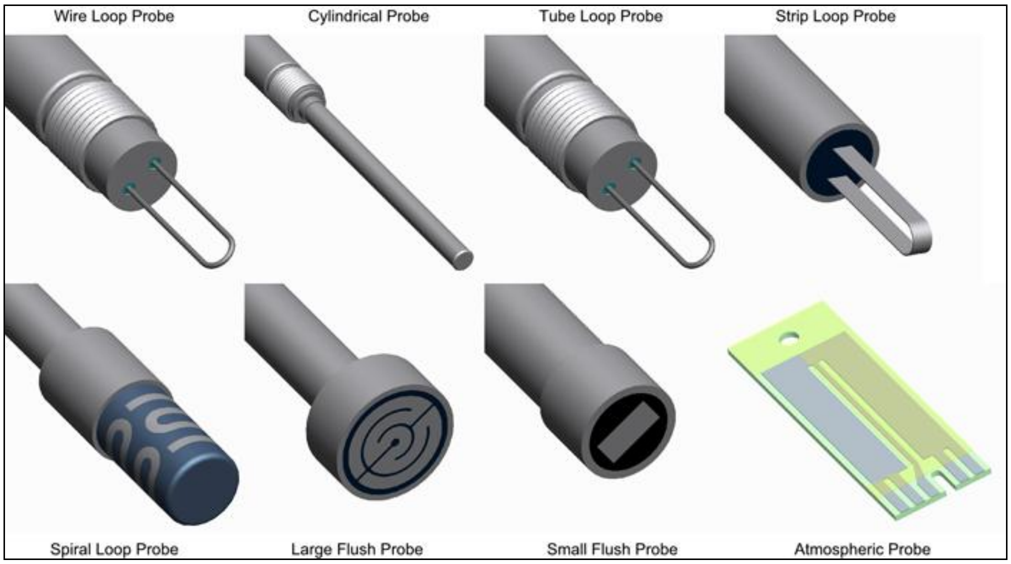

Figure 4 : ER Sensing Elements

Table 2 in the following page lists element types, thicknesses, and probe life. When selecting an element type for a given application, the key parameters in obtaining optimum results are *response time* and required *probe life*. Response time, defined as the minimum time in which a measurable change takes place, governs the speed with which useful results can be obtained. Probe life, or the time required for the effective thickness of the exposed element to be consumed, governs the probe replacement schedule.

Table 2 : Element Type, Thickness & Probe Life of ER Sensing Element

Element Type	Thickness	Probe Life
Wire loop	40 mil 80 mil	10 mil 20 mil
Tube loop	4 mil 8 mil	2 mil 4 mil
Strip loop	5 mil 10 mil	1.25 mil 2.5 mil
Cylindrical	10 mil 20 mil 50 mil	5 mil 10 mil 25 mil
Spiral loop	10 mil 20 mil	5 mil 10 mil
Flush (small)	4 mil 8 mil 20 mil	2 mil 4 mil 10 mil
Flush (large)	5 mil 10 mil 20 mil 40 mil	2.5 mil 5 mil 10 mil 20 mil
Surface Strip	10 mil 20 mil 40 mil	5 mil 10 mil 20 mil

Wire loop elements are the most common element available. This type of element has high sensitivity and low susceptibility to system noise, making it a good choice for most monitoring installations. Wire loops are generally glass-sealed into an endcap which is then welded to the probe body. The glass seal, which is chemically inert in most environments and has a good pressure and temperature rating, makes a good choice for most applications. Alloys commonly glass sealed are Carbon Steel, AISI 304 and 316 stainless steels. Probes with wire loop elements are normally equipped with a flow deflector or velocity shield to protect the element from floating debris in the piping system.

Tube loop elements are recommended where high sensitivity is required to rapidly detect low corrosion rates. Tube loop elements are manufactured from a small bore, hollow tube formed into the above loop configuration. Probes using the tubular loop element can be equipped with a flow deflector to minimize possible distortion in fast flowing systems.

Strip loop elements are similar to the wire and tube loop configurations. The strip loop is a flat element formed in a loop geometry. The strip loop may be glass or epoxy sealed into the endcap depending on the required application. The strip loop is a very sensitive element. Strip loops are very fragile and should only be considered for very low flow applications.

Cylindrical elements are manufactured by welding a reference tube inside of a tube element. This element has an all welded construction which is then welded to the probe body. This probe is ideally suited to harsh environments including high velocity and high temperature systems, or anywhere a glass-sealed element is not an option.

Spiral loop elements consist of a thin strip of metal formed on an inert base. The element is particularly rugged and ideal for high-flow regimens. Its comparatively high resistance produces a high signal-to-noise ratio, which makes the element very sensitive.

Flush mount elements are designed to be mounted flush with the vessel wall. This element is very effective at simulating the true corrosion condition along the interior surfaces of the vessel wall. Being flush, this element is not prone to damage in high velocity systems and can be used in pipeline systems that are subject to pigging operations.

Surface strip elements are thin rectangular elements with a comparatively large surface area to allow more representative results in non-homogeneous corrosive environments. Strip elements are commonly used in underground probes to monitor the effectiveness of cathodic protection currents applied to the external surfaces of buried structures [7].

CHAPTER 3

METHODOLOGY

3.1 Procedure Identification

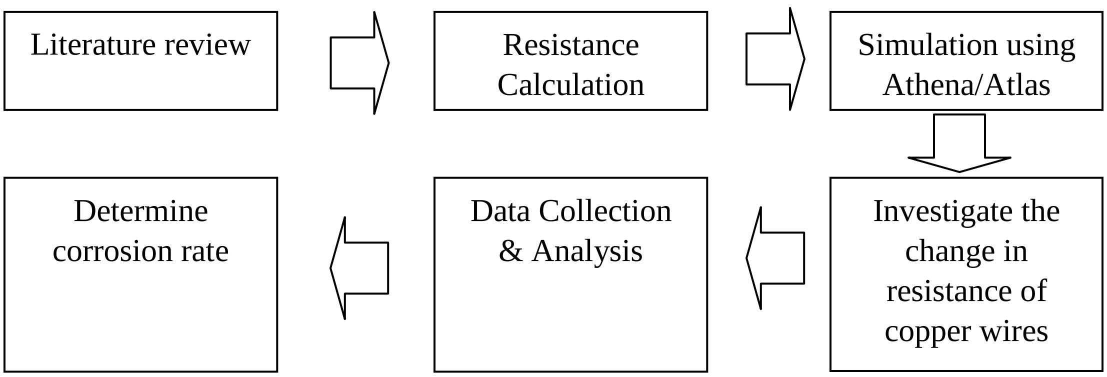

Figure 5 : Procedure Identification

Figure 5 shows the procedure identifition in implementing this project. The work begin with some literature review on corrosion as well as the available technique to monitor corrosion, especially Electrical Resistance(ER) technique. The work is proceed by calculating resistance's value for three different thicknesses of conductor and the simulation using Athena/Atlas is implemented to verify the resistance calculation. Later, this project is continued by investigating the change in resistance of immersed copper wires in corroding solution. After completing the measurement, data is collected and analysized. The last part of this project is to determine corrosion rate for each copper wires in corroding solution. The overall activities can be referred in Appendix C.

3.2 Project Activities

Before going to the investigation experimentally, the software simulation should be implemented to investigate the relation between thicknesses and electrical resistance. There are two type of software used in this simulation, called ATHENA and ATLAS

3.2.1 Simulation using Athena

Athena is a simulator that provides general capabilities, for numerical, physically based, two dimensional simulation of semiconductor processing. Figure 6 shows how the simulation of wafer fabrication is implemented.

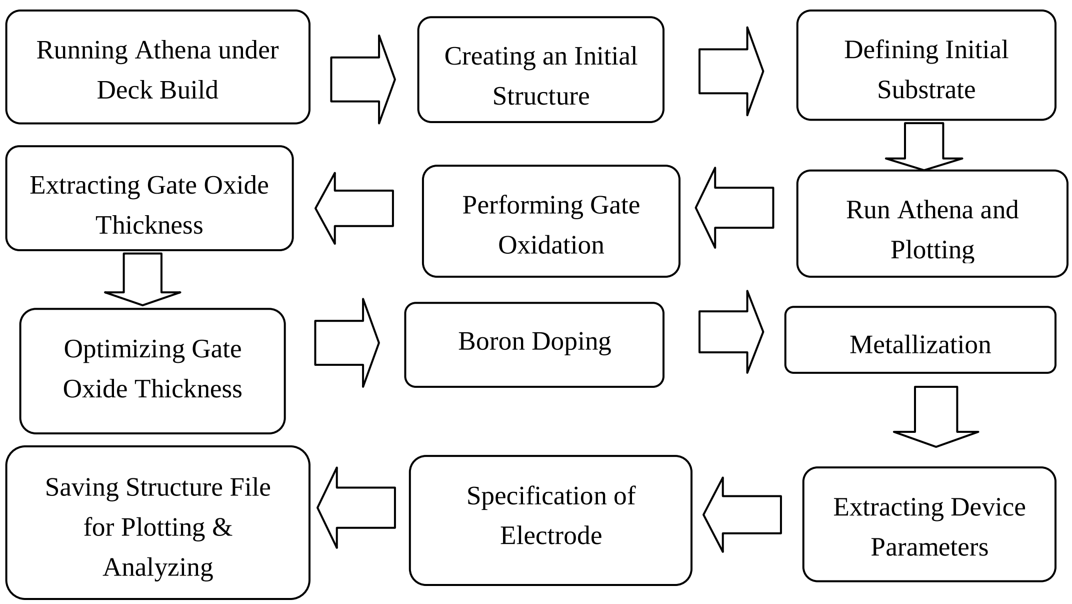

Figure 6 : Process Flow of Simulation using Athena

3.2.2 Simulation using Atlas

After completing the Athena simulation, the next step is the simulation using Atlas software. Atlas is used to obtain the I-V characteristic of the structure that is implemented using Athena. Figure 7 represents the flow of simulation using Atlas.

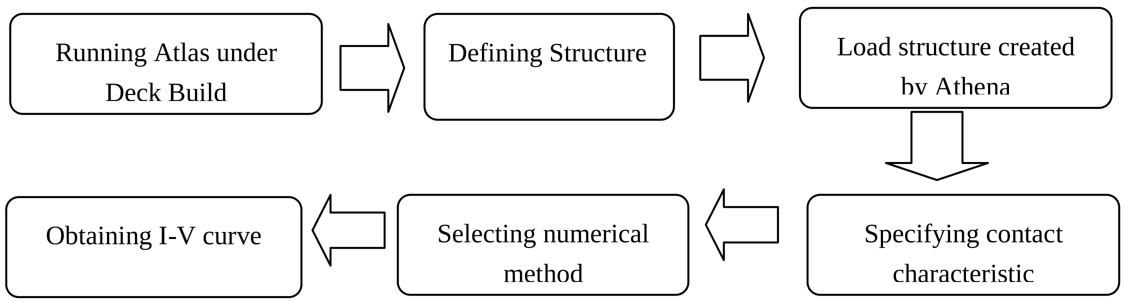

Figure 7 : Flow of Simulation using Atlas

3.2.3 Experimental Measurement

After completing the simulation, the investigation of corrosion rate using Electrical Resistance method is conducted at Nanotech laboratory. Flow chart in Figure 8 shows the process flow to investigate change in resistance of corroding wires [9]. There are certain parameters that are essential and listed below;

1. Voltage supply from picoammeter is constant.
2. Diameter and length of copper wires A, B and C are obtained first.
3. Initial Salinity of Sodium Chloride (3.5%) and need to be increased if necessary.

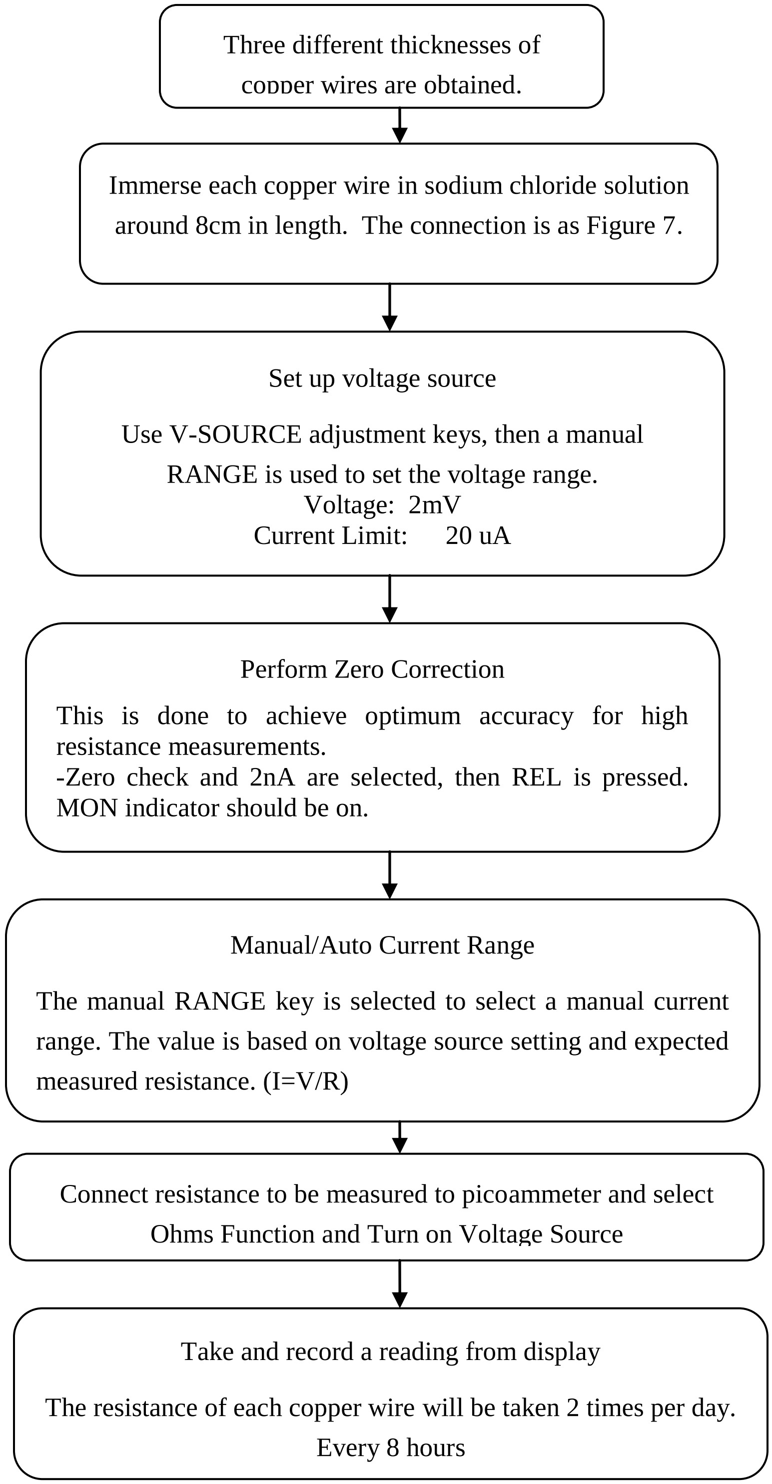

Figure 8 : Process Flow to Investigate Change in Resistance of Corroding Wires

3.3 Tools and Equipment Required

In order to perform the measurement, several devices and equipments had been used. The equipments are listed below and the connection of these equipments in laboratory can be referred at Figure 6.

- Picoammeter Keithley 6487
- Crocodile Clips
- Beaker (500 ml)
- Sodium Chloride, NaCI(Salt)
- Copper Wires with 3 different thicknesses

Figure 9 shows the connection of electrical resistance measurement for first copper wire (0.048 cm in diameter). The reading of measurement is displayed at Picoammeter. The same connection is applied to measure resistance for second and third copper wire (0.050cm 0.020cm in diameter respectively). The connection of these equipment in laboratory can be referred in Appendix A.

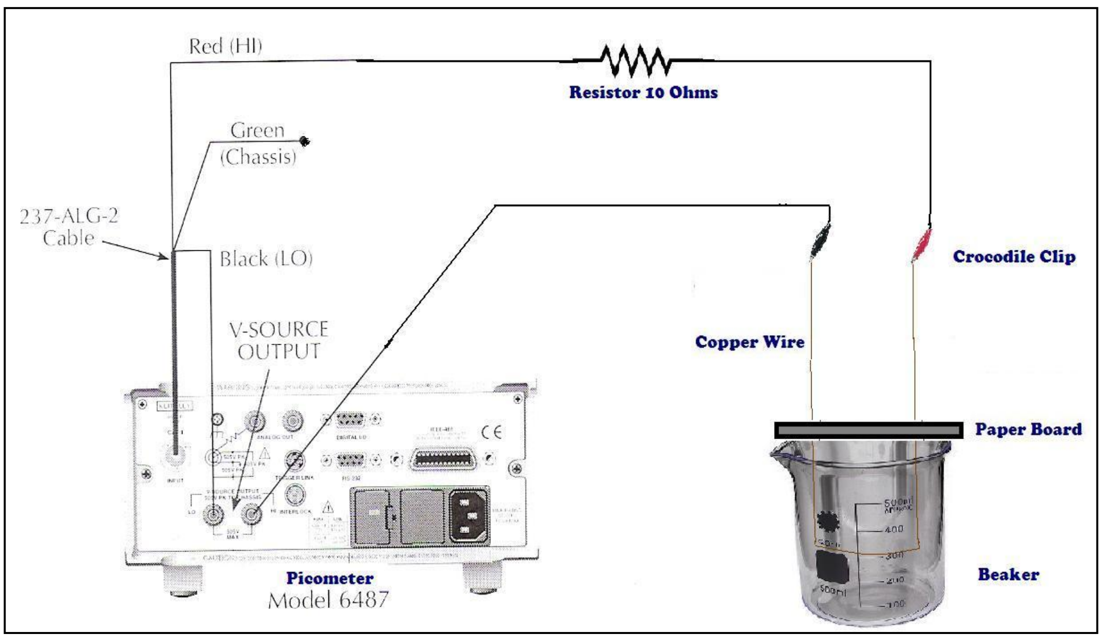

Figure 9 : Connection of Equipments/Devices Used

CHAPTER 4
RESULT AND DISCUSSIONS

4.1 Simulation Using Athena & Atlas

The purpose of this simulation is to investigate the relationship between resistance and thickness of conductor. The simulation started with deposit titanium structure on silicon oxide. Then, IV curve is obtained by running Atlas's simulation. The result of this simulation will be analyzed in the following section. Figure 10 represent the result of Athena's simulation with length of titanium is 70µm and its thickness is 0.8µm. Figure 11 shows represents amount of current passing through the region of titanium.

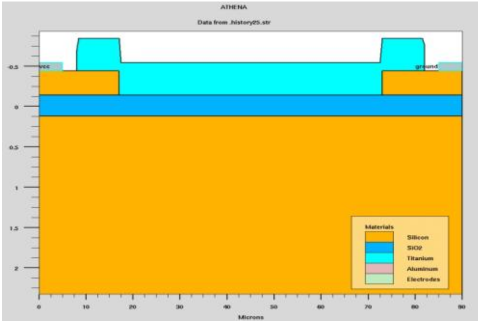

Figure 10 : Initial Titanium Structure Part I

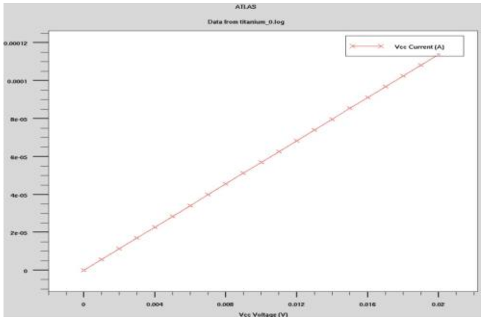

Figure 11 : IV curve for titanium's thickness Part I

For Part II of Athena's simulation, as can be seen in Figure 12, the region of titanium is reduced until its thickness reaches 0.54µm while its length is still 70µm as shown in Figure 12. IV curve in Figure 13 represents amount of current passing through the region of titanium.

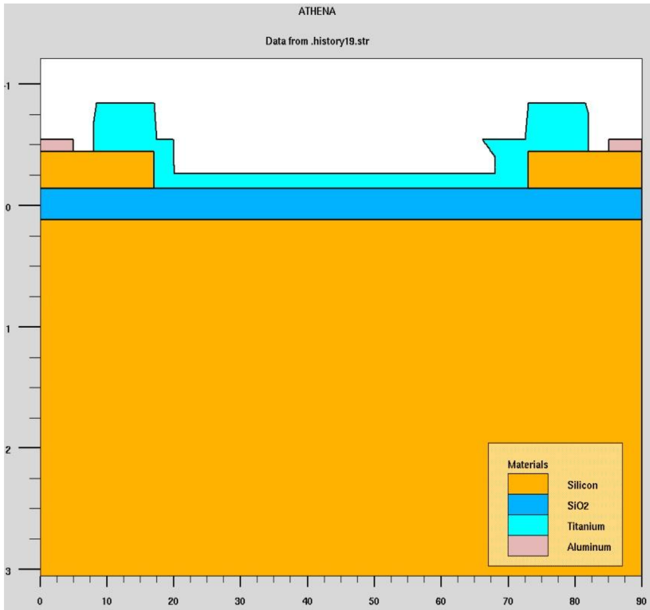

Figure 12 :Thickness of titanium Part II

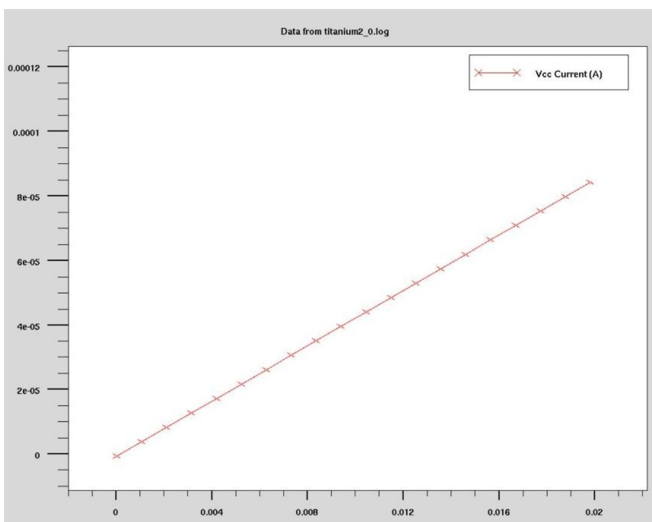

Figure 13 :IV curve for 0.26um titanium's thickness Part II

For Part III of Athena's simulation, as can be seen in Figure 14, the region of titanium is reduced until its thickness reaches 0.18µm while its length is still 70µm as shown in Figure 14. IV curve in Figure 15 represents amount of current passing through the region of titanium.

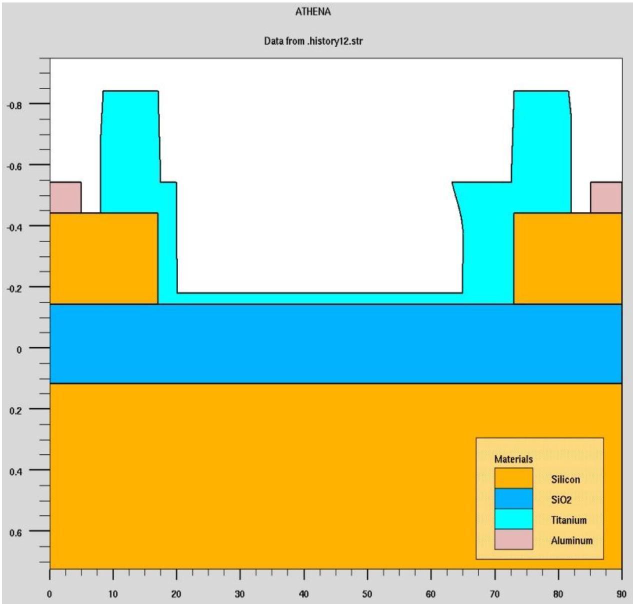

Figure 14 : Thickness of titanium Part III

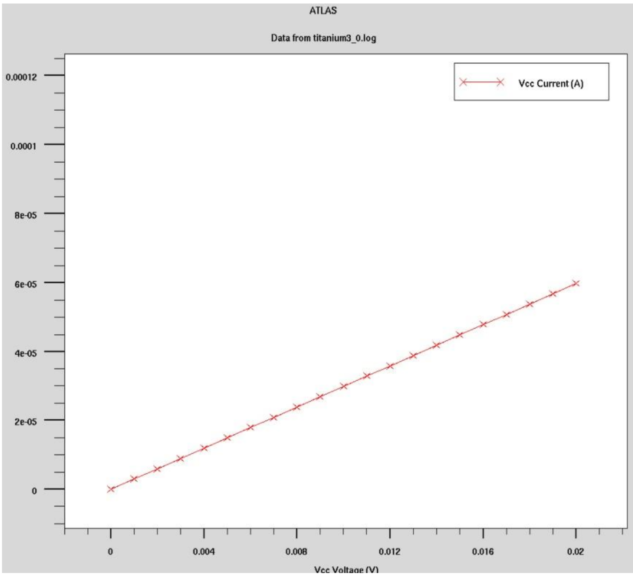

Figure 15 : IV curve for titanium's thickness Part III

4.1.1 Data Analyzing for Simulation (Part I)

For the IV curve for the first part of the simulation, the current is increasing proportionally when the voltage increase. The thickness of the titanium structure is equal to 0.8 µm. The slope (m) of the graph is equal to $y = mx$, where y represents current and x represents voltage. The calculation to find the slope, *m* is as per below;

$$m = \frac{(X\,\mathrm{max} - X\,\mathrm{min})A}{(Y\,\mathrm{max} - Y\,\mathrm{min})V}$$

$$= \frac{(0.00017346 - 0)A}{(0.022304 - 0)V} = 7.777 \times 10^{-3} \text{ Ohms}$$

Based on Ohm's Law:

I = V/R,
I: current
V: voltage
R: resistance

So, the slope of the line above is $\frac{1}{R}$. [This follows from comparison of $I = \frac{V}{R}$ and $y = mx$, a direct proportionality, where m is the slope or proportionality constant of the linear relationship (straight line) [11].

$$R = \frac{1}{7.777 \times 10^{-3} A/V}$$

= **<u>128.58 Ohms</u>**

4.1.2 Data Analyzing for Simulation (Part II)

After etching some area of the titanium region, the thickness of titanium is 0.54 µm. If we relate to the Ohm's Law that defines V=IR, this smaller value of current I is caused by increasing of resistance at that region. From the graph, the electrical resistance, $R = \frac{1}{m}$. The calculation of slope is as per below;

$$m = \frac{(X\max - X\min)A}{(Y\max - Y\min)V}$$

$$= \frac{(8.25\times10^{-5} - 0)A}{(0.022304 - 0)V} = 3.699\times10^{-3} \text{ Ohms}$$

$$R = \frac{1}{m} = \frac{1}{3.699\times10^{-5}\times10^{-3}} = \underline{\mathbf{270.35\ Ohms}}$$

4.1.3 Data Analyzing for Simulation (Part III)

For the last part of the simulation, with thickness of titanium of 0.18µm, it can be seen that the slope of the IV curve has changed little bit. By using Ohm's Law, the value of resistance could be obtained. The slope of the graph is as per below;

$$m = \frac{(X\max - X\min)A}{(Y\max - Y\min)V} = \frac{(6\times10^{-5} - 0)A}{(0.022304 - 0)V} = 2.69\times10^{-3} A/V$$

$$R = \frac{1}{m} = \frac{1}{2.69\times10^{-3} A/V} = \underline{\mathbf{371.73\ Ohms}}$$

4.2 Discussion on Simulation of Athena & Atlas

According to the relation between resistance and thickness of materials as shown in the equation below;

$$R = \frac{\rho L}{A}$$

When the length is constant, the value of the resistance depends on area of cross sectional area (A). This cross sectional area depends on the thickness of the material. According to the above equation, when cross sectional area (A) decrease, the value of resistance R will also increase. Later, if we relate it with the Ohms Law (V=IR), bigger resistance results in smaller value of current. Due to this reason, that's why the value of current of the last part of this simulation is the lowest one when the same value of voltage is supplied. The resistance of 371.73 Ohms is the highest resistance compared with the resistance of the first and second part of the simulation. This is happened because of the decreasing of cross sectional area (A) of titanium structure. For summary, as shown in Figure 16, the decreasing in thickness results in increasing in resistance, where

T3>T2>T1 that result in R1>R2>R3

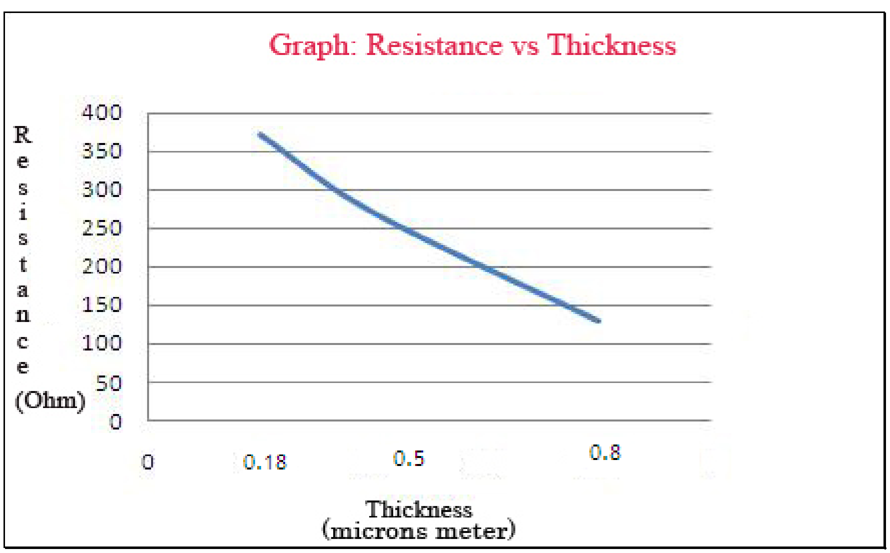

Figure 16 : Graph for resistance versus thickness

4.3 Measurement of Electrical Resistance in Corroding Solution

4.3.1 Specification of Wires

Diameter of copper wires is obtained by using micrometer. The details are shown in Table 3 below.

Table 3 : Specification of Wires

Copper Wire	Resistivity (ohm cm)	Length (cm)	Diameter (cm)	Cross Sectional Area (cm²)	Theoretical Resistance (Ohms)
A	1.68×10^{-6}	30	0.048	1.81×10^{-3}	0.0278
B	1.68×10^{-6}	30	0.050	1.96×10^{-3}	0.0257
C	1.68×10^{-6}	30	0.020	0.314×10^{-3}	0.1605

Area of thickness is equal to $A = \pi r^2$

By using the parameters at Table 1, the theoretical resistance is calculated form equation:

$$R = \frac{\rho L}{A}$$

ρ = resistivity
L = length
A = cross sectional area

The theoretical value of resistances is the resistance produced when current flow through the wires. This value of resistance is not included 10 Ohms value of Rs.

The investigation started on 28th July 2009 where each copper wire had been immersed in corroding solution that has 3.5% salinity of water and the measurement by using this salinity of water was continued until 5th October 2009, make a total of 70 days.

The salinity of water had been increased to 7% on 6th October 2009 and the measurement is continued until 15th October 2009, make a total of 10 days measurement using 7% salinity of water.

4.3.2 Data Collection

The data was collected 2 times per day and the duration of this investigation is 80 days. It started from 28th July 2009 until 15th October 2009. The data was collected at 8.30am and 4.30pm. The resistor, Rs is used to limit the current pass through the resistance to avoid overflow, since the current limit is so small and not exceed 20µA while the voltage is 2mV. Table 4 in the following page shows value of resistance based on measurement that includes 10 Ohms value of Rs.

The actual resistance when the current flow through the 30 cm wires should be subtracted by 10 Ohms (Rs). Table 5 in the following page shows the actual resistance when 10Ω (resistor of Rs) is not included in calculation. This is done by subtracting the value of 10Ω Rs from the readings. Table 4 and Table 5 in the following page show the details of readings of resistances of each copper wires and the date when the readings are taken.

Table 4 : Resistance Reading for Copper Wires with 10Ω Resistor

Date	Time	Reading A (Ω)	Reading B (Ω)	Reading C (Ω)
01/08/09	8.30 am	10.0580	10.2434	13.0340
	4.30 pm	10.0345	10.3422	12.8099
02/08/09	8.30 am	11.3121	10.1941	13.6428
	4.30 pm	10.1427	11.0712	12.8520
03/08/09	8.30 am	11.2103	10.0299	14.3125
	4.30 pm	10.3410	11.2656	15.5621
04/08/09	8.30 am	10.3639	12.0182	16.0031
	4.30 pm	11.0021	12.2044	14.6301
08/09/09	8.30 am	10.2981	10.7042	14.8564
	4.30 pm	10.3235	10.5631	15.6932
09/09/09	8.30 am	10.3694	10.7736	14.7460
	4.30 pm	10.3287	10.8903	14.3748
10/09/09	8.30 am	10.9785	12.4782	14.0293
	4.30 pm	11.0814	12.5135	14.6367
30/09/09	8.30 am	10.7341	12.4971	16.6903
	4.30 pm	10.5632	12.5826	15.9955
01/10/09	8.30 am	10.7149	12.4845	15.3045
	4.30 pm	10.6583	12.619	14.4543
02/10/09	8.30 am	10.9181	12.5579	14.2745
	4.30 pm	10.8434	12.6974	15.2609
05/10/09	8.30 am	11.0491	12.6686	15.9521
	4.30 pm	11.0941	12.7535	16.0194
06/10/09	8.30 am	13.5293	14.4657	16.2244
	4.30 pm	13.322	14.9421	16.4214
07/10/09	8.30 am	13.3391	14.7015	17.4252
	4.30 pm	13.8185	14.7571	17.5242
08/10/09	8.30 am	14.0947	15.2377	17.4242
	4.30 pm	14.0061	15.4523	18.0421
09/10/09	8.30 am	14.9116	16.1186	18.1317
	4.30 pm	15.3366	16.5176	18.1542
12/10/09	8.30 am	15.4355	16.7071	18.0921
	4.30 pm	15.5145	16.759	18.4139
13/10/09	8.30 am	15.8053	16.8541	18.4513
	4.30 pm	16.1885	16.8516	18.2955
14/10/09	8.30 am	16.2087	17.1276	18.5913
	4.30 pm	16.3379	17.9543	18.6248
15/10/09	8.30 am	16.3443	17.8071	18.6244
	4.30 pm	16.5617	17.9862	18.8337

Table 5 : Resistance Reading for Copper Wires without 10Ω Resistor

Date	Time	Reading A (Ω)	Reading B (Ω)	Reading C (Ω)
01/08/09	8.30 am	0.0580	0.2434	3.0340
	4.30 pm	0.0345	0.3422	2.8099
02/08/09	8.30 am	1.3121	0.1941	3.6428
	4.30 pm	0.1427	1.0712	2.8520
03/08/09	8.30 am	1.2103	0.0299	4.3125
	4.30 pm	0.3410	1.2656	5.5621
04/08/09	8.30 am	0.3639	2.0182	6.0031
	4.30 pm	1.0021	2.2044	4.6301
08/09/09	8.30 am	0.2981	0.7042	4.8564
	4.30 pm	0.3235	0.5631	5.6932
09/09/09	8.30 am	0.3694	0.7736	4.7460
	4.30 pm	0.3287	0.8903	4.3748
10/09/09	8.30 am	0.9785	2.4782	4.0293
	4.30 pm	1.0814	2.5135	4.6367
30/09/09	8.30 am	0.7341	2.4971	6.6903
	4.30 pm	0.5632	2.5826	5.9955
01/10/09	8.30 am	0.7149	2.4845	5.3045
	4.30 pm	0.6583	2.619	4.4543
02/10/09	8.30 am	0.9181	2.5579	4.2745
	4.30 pm	0.8434	2.6974	5.2609
05/10/09	8.30 am	1.0491	2.6686	5.9521
	4.30 pm	1.0941	2.7535	6.0194
06/10/09	8.30 am	3.5293	4.4657	6.2244
	4.30 pm	3.322	4.9421	6.4214
07/10/09	8.30 am	3.3391	4.7015	7.4252
	4.30 pm	3.8185	4.7571	7.5242
08/10/09	8.30 am	4.0947	5.2377	7.4242
	4.30 pm	4.0061	5.4523	8.0421
09/10/09	8.30 am	4.9116	6.1186	8.1317
	4.30 pm	5.3366	6.5176	8.1542
12/10/09	8.30 am	5.4355	6.7071	8.0921
	4.30 pm	5.5145	6.759	8.4139
13/10/09	8.30 am	5.8053	6.8541	8.4513
	4.30 pm	6.1885	6.8516	8.2955
14/10/09	8.30 am	6.2087	7.1276	8.5913
	4.30 pm	6.3379	7.9543	8.6248
15/10/09	8.30 am	6.3443	7.8071	8.6244
	4.30 pm	6.5617	7.9862	8.8337

4.3.3 Data Analysis

From the data obtained, graph that relates the resistance of copper wires to the time is plotted in Figure 17. From the graph, it can be seen that Copper wires C has higher value of resistance compared to Copper wire A and B, since it has smallest cross sectional area.

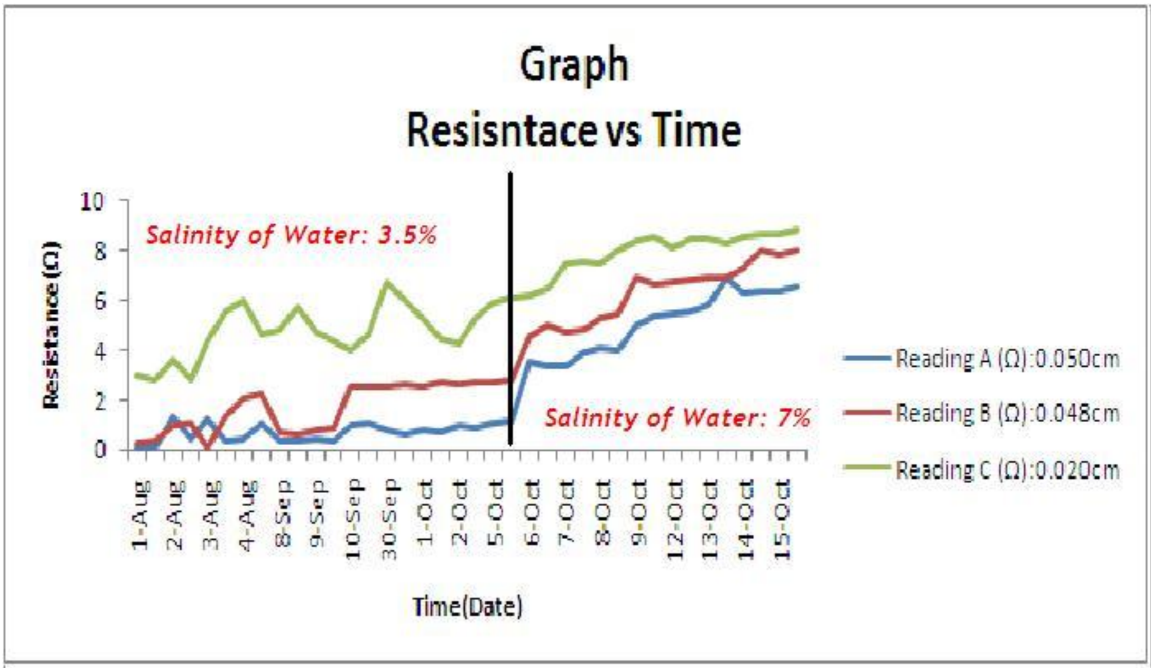

Figure 17 : Graph Resistance versus Time (Excluding 10 Ohms Resistor)

The graph also shows two difference salinity of water. For the few weeks from 1st August 2009 until 5th October 2009, the salinity of water is 3.5%. Then onwards the salinity of water is 7.0%. The purpose of increasing the salinity of water is to accelerate the corrosion process and to monitor the change in resistance due to the increase of salinity of water.

From the graph, when the salinity of water is increased to 7%, the change in resistance can be observed clearly. The corrosion rate is then calculated from these data and discussed in the following section.

Figure 18 and Figure 19 represent resistance of copper wires versus time according to the salinity of water used, 3.5% and 7% respectively. The graphs will be used to calculate corrosion rate of each wire according to their salinity of water. For salinity of 3.5%, corrosion rate can be determined by calculating the difference between R1 and R0 of each wire divided by duration of investigation. For salinity of 7.0%, corrosion rate can be determined by calculating the difference between R2 and R1 of each wire divided by duration of investigation.

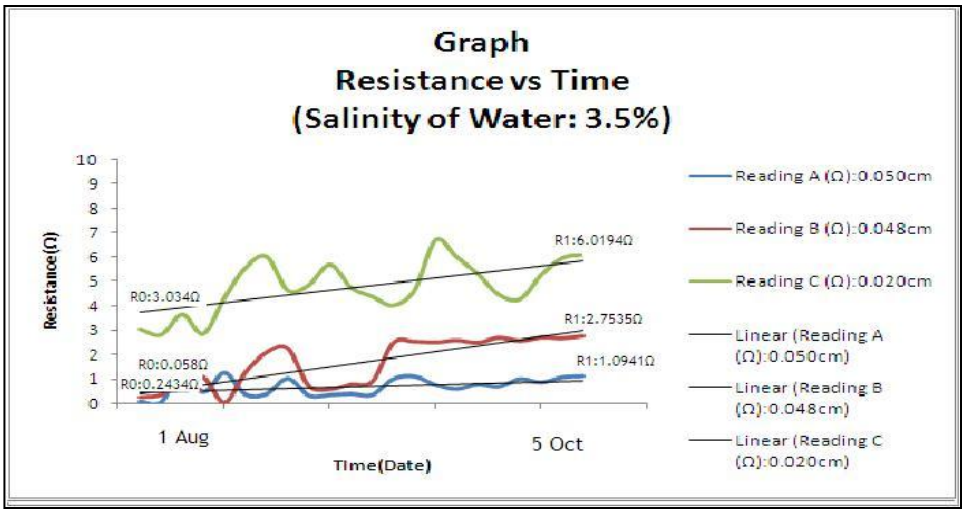

Figure 18 : Graph Resistance versus Time with Salinity of 3.5%

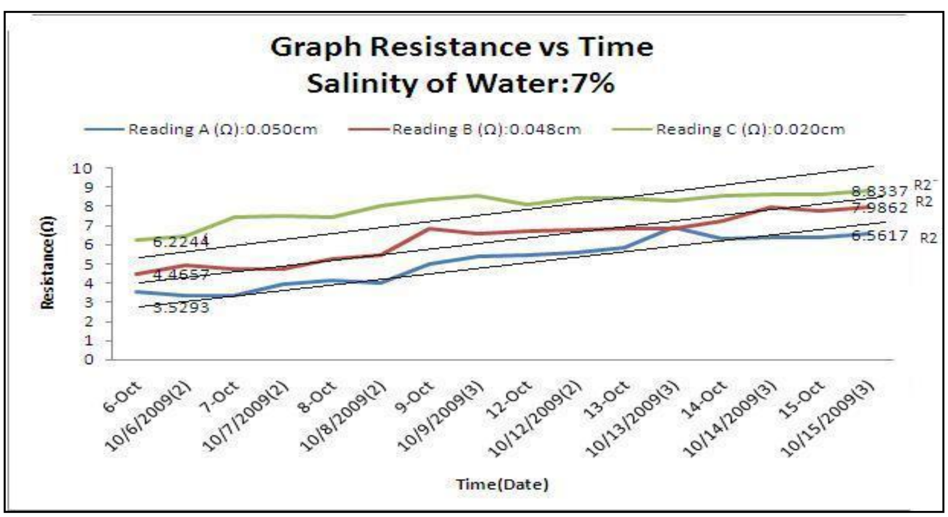

Figure 19 : Graph Resistance versus Time with Salinity of 7.0%

4.4 Discussion on Experimental Measurement of Resistance

4.4.1 Calculation of Corrosion Rate

The rate of corrosion of each copper wire can be calculated using the equation:

$$\text{Corrosion Rate} = \frac{\text{Change in diameter}}{\text{Time of investigation (days)}}$$

Copper Wire A

For 3.5% Salinity of water:

- R0: 0.0580Ω
- R1: 1.0941Ω

From Figure 18

$$R1 - R0 = 1.0941\Omega - 0.0580\Omega = 1.0361\Omega$$

$$\Delta R = \frac{\rho L}{\Delta A} = \frac{1.68\times10^{-6}\Omega.cm \times 30cm}{\Delta A} = 1.0361\Omega$$

$$\Delta A = \prod r^2 = \frac{\rho L}{\Delta R} = \frac{1.68\times10^{-6}\Omega.cm \times 30cm}{1.0361\Omega} = 4.864\times10^{-5}cm^2$$

$$\Delta r^2 = \frac{4.864\times10^{-5}cm^2}{\prod} = 1.548\times10^{-5}cm^2$$

$$\Delta r = \sqrt{1.548\times10^{-5}cm^2} = 0.00393cm$$

$$\Delta d = 2r = 2\times0.00393cm = 0.00787cm$$

Rate of Corrosion

$$\frac{\Delta Diameter}{Time} = \frac{0.00787cm}{70days}$$
$$= 1.124\times10^{-4}\,cm/day$$
$$\approx 410\,\mu m/year$$

For 7% Salinity of water:

- R1: 1.0941Ω
- R2: 6.5616Ω

From Figure 19

$$R1 - R2 = 6.5616\Omega - 1.0941\Omega = 5.4675\Omega$$

$$\Delta R = \frac{\rho L}{\Delta A} = \frac{1.68\times10^{-6}\Omega.cm \times 30cm}{\Delta A} = 5.4675\Omega$$

$$\Delta A = \prod r^2 = \frac{\rho L}{\Delta R} = \frac{1.68\times10^{-6}\Omega.cm \times 30cm}{5.4675\Omega} = 9.218\times10^{-6}cm^2$$

$$\Delta r^2 = \frac{9.218\times10^{-6}cm^2}{\prod} = 2.9342\times10^{-6}cm^2$$

$$\Delta r = \sqrt{2.9342\times10^{-6}cm^2} = 0.00713cm$$

$$\Delta d = 2r = 2\times0.00713cm = 0.00342cm$$

Rate of Corrosion

$$\frac{\Delta Diameter}{Time} = \frac{0.00342cm}{10days}$$
$$= 3.426\times10^{-4}\,cm/day$$
$$\approx 1250\,\mu m/year$$

Copper Wire B

For 3.5% Salinity of water:

- R0: 0.2434Ω
- R1: 2.7535Ω

From Figure 18

$$R1 - R0 = 2.7535\Omega - 0.2424\Omega = 2.5111\Omega$$

$$\Delta R = \frac{\rho L}{\Delta A} = \frac{1.68 \times 10^{-6}\Omega.cm \times 30cm}{\Delta A} = 2.5111\Omega$$

$$\Delta A = \prod r^2 = \frac{\rho L}{\Delta R} = \frac{1.68 \times 10^{-6}\Omega.cm \times 30cm}{2.5111\Omega} = 2.008 \times 10^{-5} cm^2$$

$$\Delta r^2 = \frac{2.008 \times 10^{-5} cm^2}{\prod} = 6.389 \times 10^{-5} cm^2$$

$$\Delta r = \sqrt{6.389 \times 10^{-5} cm^2} = 0.00258cm$$

$$\Delta d = 2\Delta r = 2 \times 0.00258cm = 0.00506cm$$

Rate of Corrosion

$$\frac{\Delta Diameter}{Time} = \frac{0.00506cm}{70days}$$
$$= 7.22 \times 10^{-5} cm/day$$
$$\approx 264 \mu m/year$$

For 7% Salinity of water:

- R1: 7.9862Ω
- R2: 2.7535Ω

From Figure 19

$$R2 - R1 = 7.9862\Omega - 2.735\Omega = 5.2512\Omega$$

$$\Delta R = \frac{\rho L}{\Delta A} = \frac{1.68 \times 10^{-6}\Omega.cm \times 30cm}{\Delta A} = 5.2512\Omega$$

$$\Delta A = \prod r^2 = \frac{\rho L}{\Delta R} = \frac{1.68 \times 10^{-6}\Omega.cm \times 30cm}{5.2512\Omega} = 9.5978 \times 10^{-6} cm^2$$

$$\Delta r^2 = \frac{9.5978 \times 10^{-6} cm^2}{\prod} = 3.055 \times 10^{-5} cm^2$$

$$\Delta r = \sqrt{3.055 \times 10^{-5} cm^2} = 0.00175cm$$

$$\Delta d = 2r = 2 \times 0.00175cm = 0.0035cm$$

Rate of Corrosion

$$\frac{\Delta Diameter}{Time} = \frac{0.0035cm}{10days}$$
$$= 3.49 \times 10^{-4} cm/day$$
$$\approx 1274 \mu m/year$$

Copper Wire C

For 3.5% Salinity of water:

- R0: 3.0340Ω
- R1: 6.0194Ω

From Figure 18

$$R1 - R0 = 6.0194\Omega - 3.0340\Omega = 2.9854\Omega$$

$$\Delta R = \frac{\rho L}{\Delta A} = \frac{1.68 \times 10^{-6}\Omega.cm \times 30cm}{\Delta A} = 2.9854\Omega$$

$$\Delta A = \prod r^2 = \frac{\rho L}{\Delta R} = \frac{1.68 \times 10^{-6}\Omega.cm \times 30cm}{2.9854\Omega} = 1.688 \times 10^{-5} cm^2$$

$$\Delta r^2 = \frac{1.688 \times 10^{-5} cm^2}{\prod} = 5.374 \times 10^{-6} cm^2$$

$$\Delta r = \sqrt{5.374 \times 10^{-6} cm^2} = 0.00232cm$$

$$\Delta d = 2r = 2 \times 0.00232cm = 0.00464cm$$

Rate of Corrosion

$$\frac{\Delta Diameter}{Time} = \frac{0.00464cm}{70days}$$
$$= 6.623 \times 10^{-5} cm/day$$
$$\approx 242\mu m/year$$

For 7% Salinity of water:

- R1: 6.0194Ω
- R2: 8.8337Ω

From Figure 19

$$R2 - R1 = 8.8337\Omega - 6.0194\Omega = 2.8143\Omega$$

$$\Delta R = \frac{\rho L}{\Delta A} = \frac{1.68 \times 10^{-6}\Omega.cm \times 30cm}{\Delta A} = 2.8143\Omega$$

$$\Delta A = \prod r^2 = \frac{\rho L}{\Delta R} = \frac{1.68 \times 10^{-6}\Omega.cm \times 30cm}{2.8143\Omega} = 1.791 \times 10^{-5} cm^2$$

$$\Delta r^2 = \frac{1.791 \times 10^{-5} cm^2}{\prod} = 5.7 \times 10^{-6} cm^2$$

$$\Delta r = \sqrt{5.7 \times 10^{-6} cm^2} = 0.00239cm$$

$$\Delta d = 2r = 2 \times 0.00175cm = 0.0048cm$$

Rate of Corrosion

$$\frac{\Delta Diameter}{Time} = \frac{0.0048cm}{10days}$$
$$= 4.775 \times 10^{-4} cm/day$$
$$\approx 1743\mu m/year$$

Summary of the investigation using Copper Wire A, B, and C is shown in Table 6 below: From Table 6, it clearly shows that the rate of corrosion of each copper wire in 7% salinity of water is much greater that rate of corrosion of copper wires in 3.5% salinity of water.

Table 6 : Corrosion Rate of Copper Wires

Copper Wire	Diameter(cm)	Corrosion Rate for 3.5% Salinity of Water (µm/year)	Corrosion Rate for 7% Salinity of Water (µm/year)
A	0.048	410	1250
B	0.050	264	1274
C	0.020	242	1743

From the literature, typical corrosion rate for copper in NaCI with 3.5% salinity is around 100µm/year to 150µm/year. The result that we have obtained is slightly higher that typical corrosion rate. This may be due to some errors during the measurement. The first error could be the change in salinity of water when the volume of water getting reduces from day to day. The second error could be the disability of the picoammeter to display the readings of measurement accurately. This is happened when the equipment is not connected properly.

CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The basic theory in implementing this project using electrical resistance (ER) method was investigated. The investigation on corrosion is based on the change of electrical resistance of three copper wires A B, and C with different diameters. The theoretical and actual value of resistance was compared. Based on Ohm's Law, when the same voltage is supplied, the bigger the resistance results in decreasing of current flow. From the analysis, it clearly show that corrosion rate of copper wires in 7% salinity of water is bigger than corrosion rate of copper wires in 3.5% salinity of water. From the data analyzing, it proves the theory that said the value of resistance depends on cross sectional area. However, the rate of corrosion of copper wires may be wrong if compared to the standard corrosion rate of copper wires when 3.5% salinity of water is used. The corrosion rate of copper wires in 3.5% salinity of water should be around 100µm/year.

5.2 Recommendation

The rate of corrosion of copper wires can be corrected. This is done by monitoring and ensuring that the volume of water is always in correct amount in order to ensure the salinity of water won't change. Furthermore, it is recommended to have a data acquisition system in order to collect the data consistently, accurately and avoiding from human mistake while taking the reading. By using data acquisition system, the reading will be collected consistently, periodically, and automatically transfer the data into the computer.

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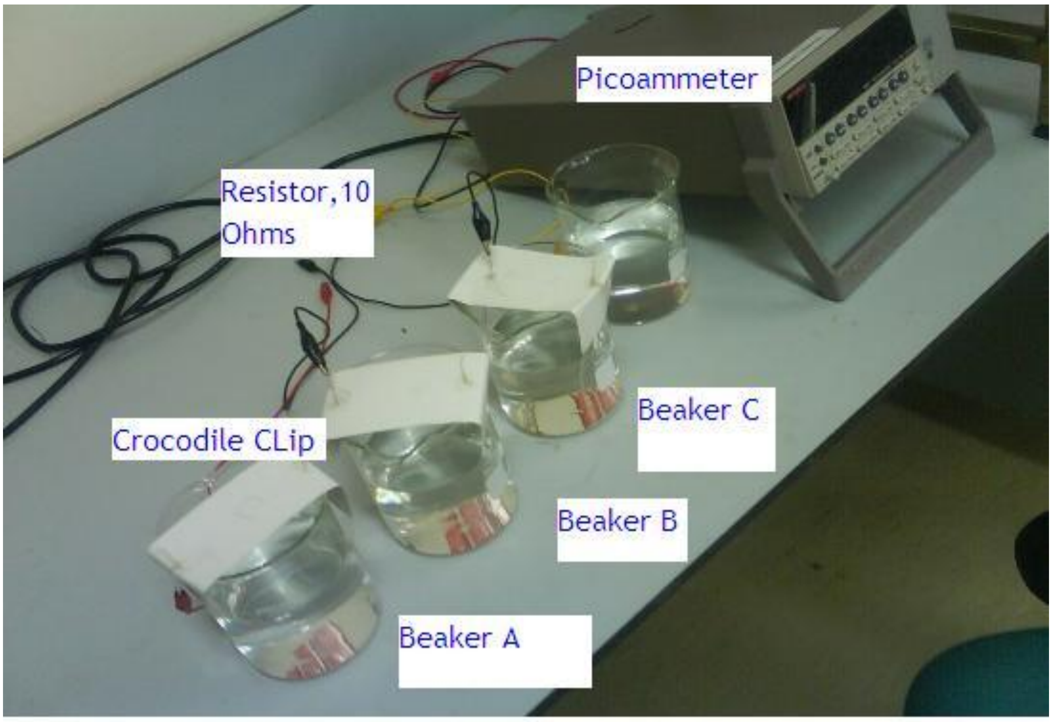
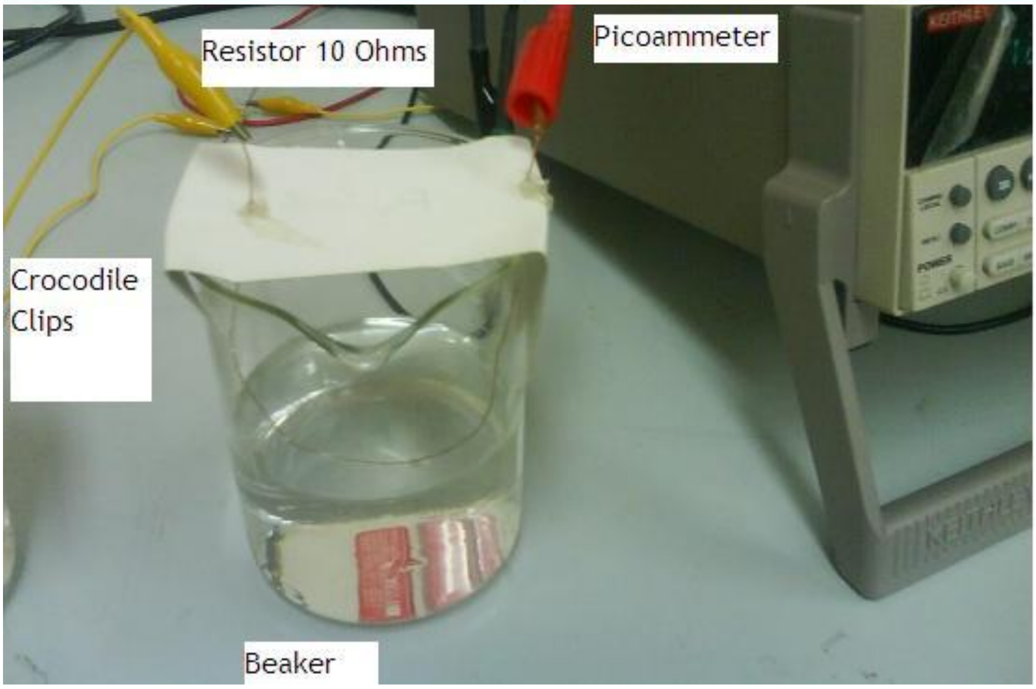
APPENDICES

APPENDIX A
CONNECTION OF EQUIPMENT

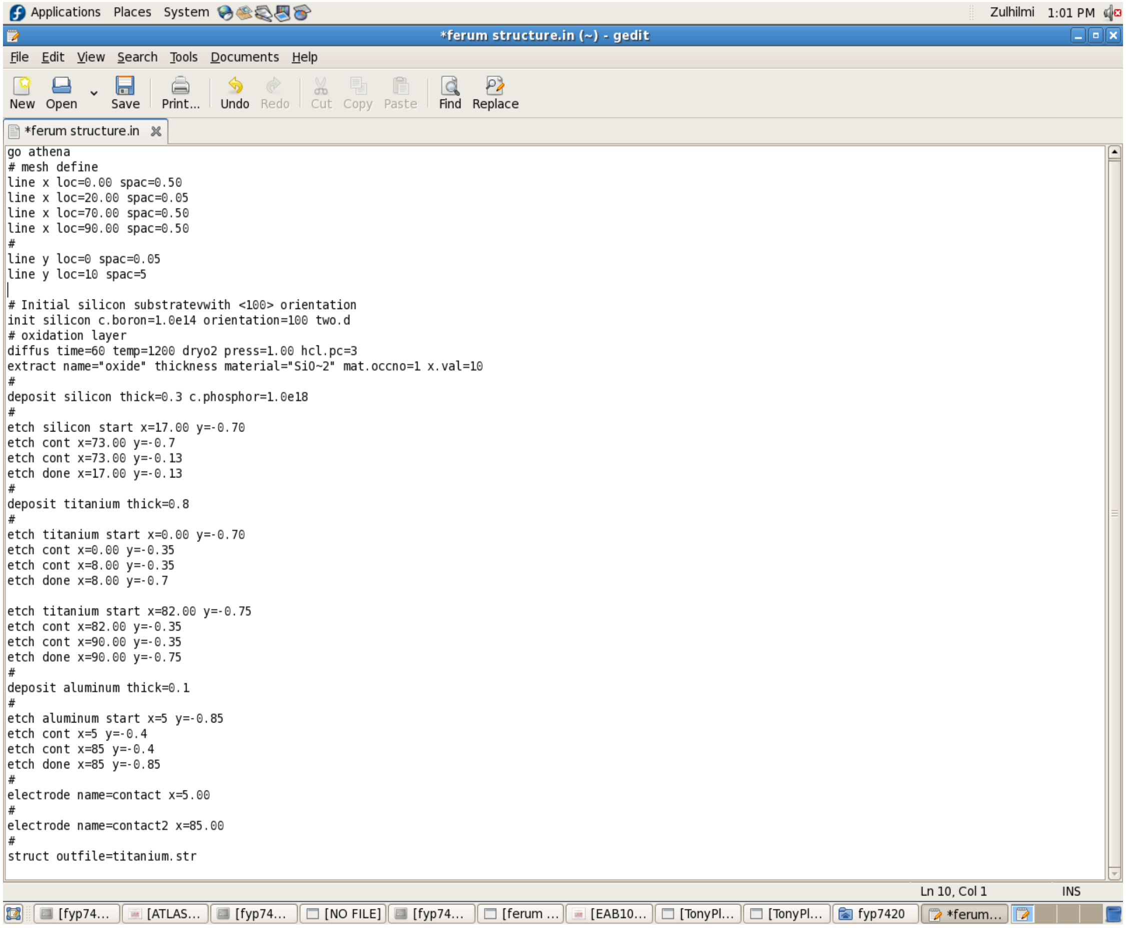




APPENDIX B

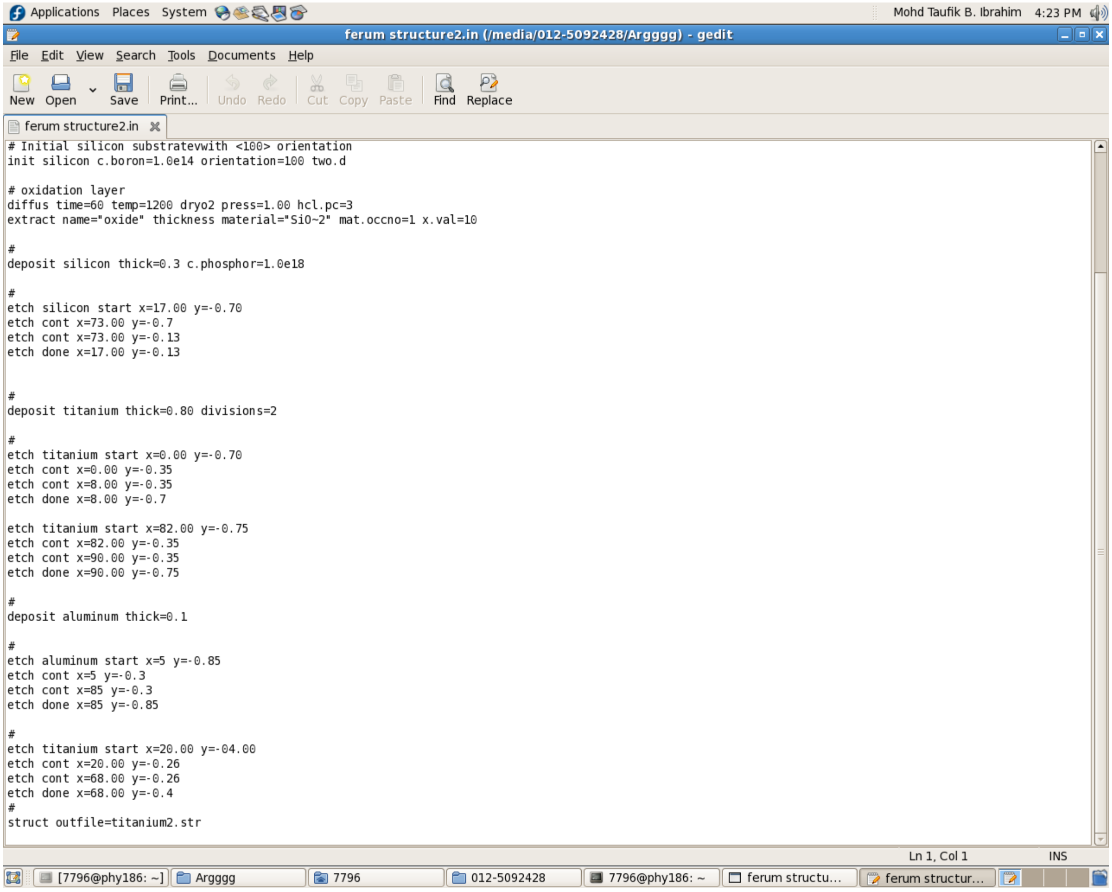
COMMAND FOR ATLAS SIMULATION

Simulation of Athena Part 1



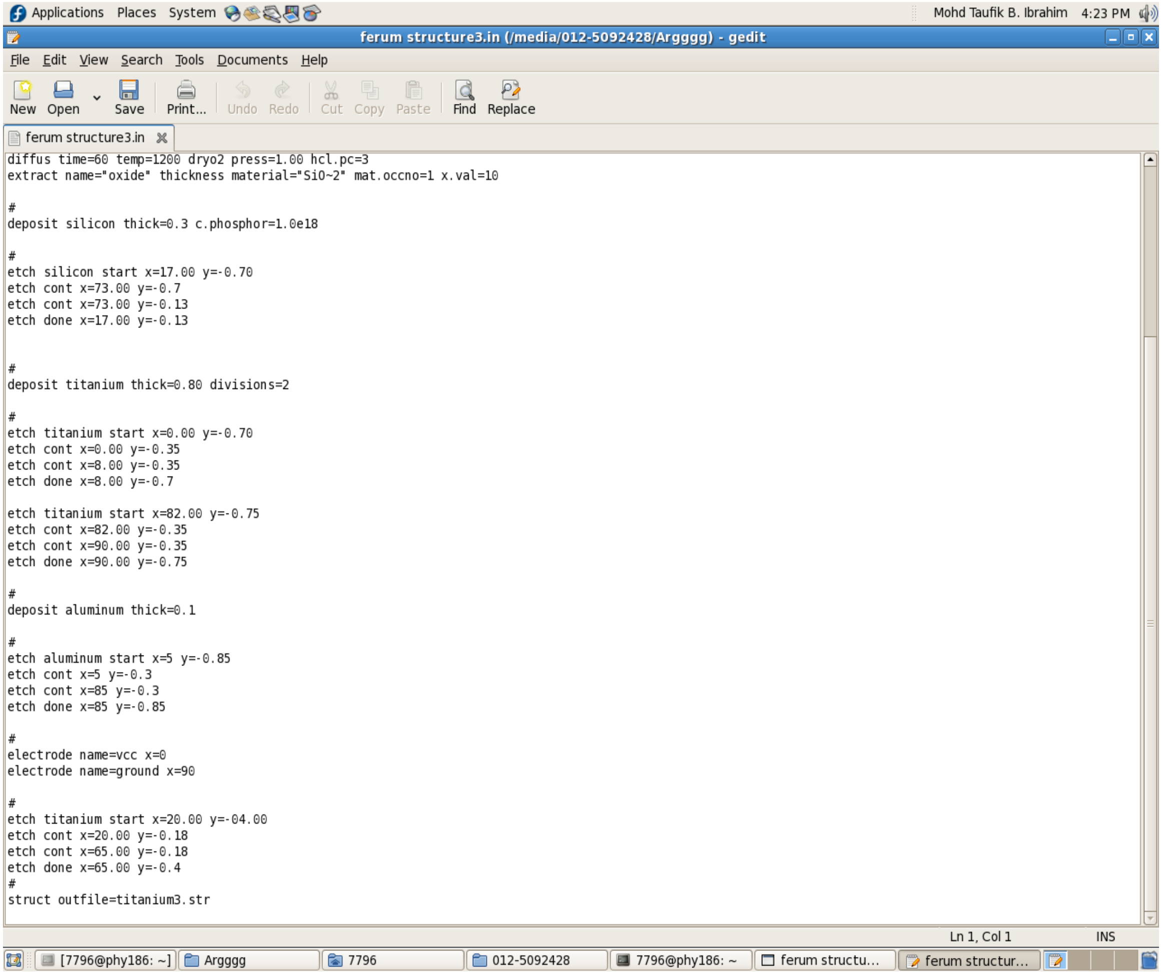
```
go athena
# mesh define
line x loc=0.00 spac=0.50
line x loc=20.00 spac=0.05
line x loc=70.00 spac=0.50
line x loc=90.00 spac=0.50
#
line y loc=0 spac=0.05
line y loc=10 spac=5

# Initial silicon substratevwith <100> orientation
init silicon c.boron=1.0e14 orientation=100 two.d
# oxidation layer
diffus time=60 temp=1200 dryo2 press=1.00 hcl.pc=3
extract name="oxide" thickness material="SiO~2" mat.occno=1 x.val=10
#
deposit silicon thick=0.3 c.phosphor=1.0e18
#
etch silicon start x=17.00 y=-0.70
etch cont x=73.00 y=-0.7
etch cont x=73.00 y=-0.13
etch done x=17.00 y=-0.13
#
deposit titanium thick=0.8
#
etch titanium start x=0.00 y=-0.70
etch cont x=0.00 y=-0.35
etch cont x=8.00 y=-0.35
etch done x=8.00 y=-0.7

etch titanium start x=82.00 y=-0.75
etch cont x=82.00 y=-0.35
etch cont x=90.00 y=-0.35
etch done x=90.00 y=-0.75
#
deposit aluminum thick=0.1
#
etch aluminum start x=5 y=-0.85
etch cont x=5 y=-0.4
etch cont x=85 y=-0.4
etch done x=85 y=-0.85
#
electrode name=contact x=5.00
#
electrode name=contact2 x=85.00
#
struct outfile=titanium.str
```

Simallation of Athena Part II




```
# Initial silicon substratevwith <100> orientation
init silicon c.boron=1.0e14 orientation=100 two.d

# oxidation layer
diffus time=60 temp=1200 dryo2 press=1.00 hcl.pc=3
extract name="oxide" thickness material="SiO~2" mat.occno=1 x.val=10

#
deposit silicon thick=0.3 c.phosphor=1.0e18

#
etch silicon start x=17.00 y=-0.70
etch cont x=73.00 y=-0.7
etch cont x=73.00 y=-0.13
etch done x=17.00 y=-0.13


#
deposit titanium thick=0.80 divisions=2

#
etch titanium start x=0.00 y=-0.70
etch cont x=0.00 y=-0.35
etch cont x=8.00 y=-0.35
etch done x=8.00 y=-0.7

etch titanium start x=82.00 y=-0.75
etch cont x=82.00 y=-0.35
etch cont x=90.00 y=-0.35
etch done x=90.00 y=-0.75

#
deposit aluminum thick=0.1

#
etch aluminum start x=5 y=-0.85
etch cont x=5 y=-0.3
etch cont x=85 y=-0.3
etch done x=85 y=-0.85

#
etch titanium start x=20.00 y=-04.00
etch cont x=20.00 y=-0.26
etch cont x=68.00 y=-0.26
etch done x=68.00 y=-0.4
#
struct outfile=titanium2.str
```

Simulation of Athena Part III

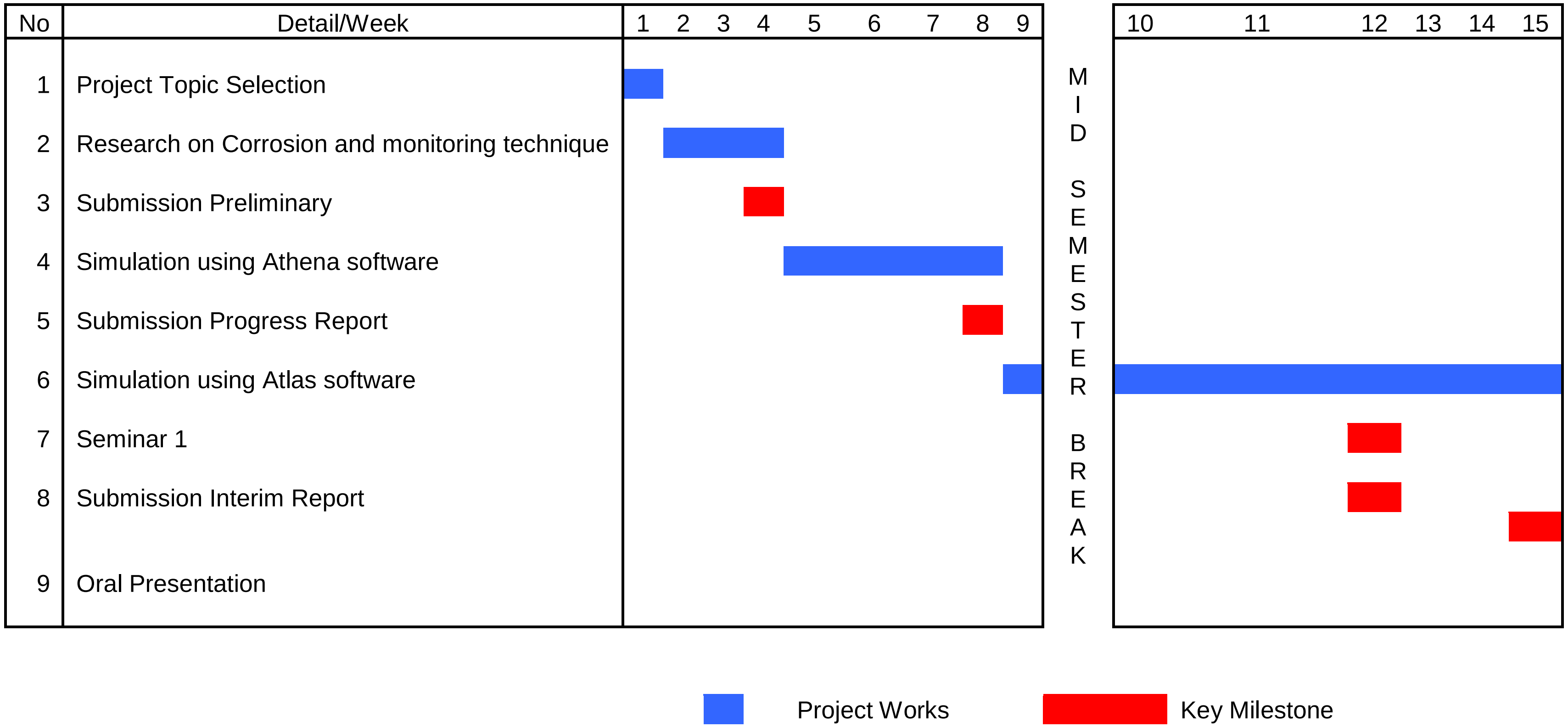



```
diffus time=60 temp=1200 dryo2 press=1.00 hcl.pc=3
extract name="oxide" thickness material="SiO~2" mat.occno=1 x.val=10

#
deposit silicon thick=0.3 c.phosphor=1.0e18

#
etch silicon start x=17.00 y=-0.70
etch cont x=73.00 y=-0.7
etch cont x=73.00 y=-0.13
etch done x=17.00 y=-0.13


#
deposit titanium thick=0.80 divisions=2

#
etch titanium start x=0.00 y=-0.70
etch cont x=0.00 y=-0.35
etch cont x=8.00 y=-0.35
etch done x=8.00 y=-0.7

etch titanium start x=82.00 y=-0.75
etch cont x=82.00 y=-0.35
etch cont x=90.00 y=-0.35
etch done x=90.00 y=-0.75

#
deposit aluminum thick=0.1

#
etch aluminum start x=5 y=-0.85
etch cont x=5 y=-0.3
etch cont x=85 y=-0.3
etch done x=85 y=-0.85

#
electrode name=vcc x=0
electrode name=ground x=90

#
etch titanium start x=20.00 y=-04.00
etch cont x=20.00 y=-0.18
etch cont x=65.00 y=-0.18
etch done x=65.00 y=-0.4
#
struct outfile=titanium3.str
```

APPENDIX C

PROJECT MILESTONE

Project Milestone Part I



Project Milestone Part II

No.	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Measurement of Electrical Resistance of Copper Wires														
2	Submission of Progress Report														
5	Seminar (compulsory)														
5	Data Gathering to Find Corrosion Rate														
6	Poster Exhibition														
7	Submission of Dissertation (soft bound)														
8	Oral Presentation														
9	Submission of Project Dissertation (Hard Bound)														

Process/Suggested Milestone