Experimental Assessment on Corrosion under Insulation (CUI)

by

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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Approved by,

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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 SYAHMI BIN RAMLI

ABSTRACT

Corrosion under insulation (CUI) is a great concern to the petroleum, gas and chemical processing plant. Due to nature of the corrosion is hidden beneath the insulation, the detection by conventional non destructive test methods is unreliable. Current practice to maintain the reliability of in plant equipments is through the implementation of Risk Based Inspection (RBI). However, the scarcity data of CUI causes difficulties in Risk Based Inspection (RBI) analysis. The objective of the project is to generate experimental data representing CUI in the marine environment, following the guidelines in API 581. The test will be based on the newly published ASTM G189-07 Standard Guide for Laboratory Simulation of Corrosion under insulation. The CUI test cell is fabricated based on ASTM G189-07 and experiments were conducted using two different techniques, which are Linear Polarization Resistance (LPR) and Weight Loss methods. Several experiments have been conducted to measure the corrosion rate at different temperatures from 60, 70, 80, and 90 Celsius. For the test at 60^0C and 70^0C , both LPR and weight loss methods resulted in the average corrosion rate of 0.18mm/yr as compared to the API 58, where the corrosion rate is 0.13mm/yr. However, for test at 80^0C and 90^0C, the experimental results are in good agreement with data in the API 58. In conclusion, experimental assessment of corrosion under insulation based on ASTM G189-07 produced good agreement with the data published in API 581.

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CHAPTER 1
INTRODUCTION

1.1 Background of Study

Corrosion under Insulation (CUI) has been a great concern to the operators of petroleum, gas and chemical processing plant. The seriousness and the aggressiveness of corrosion attack beneath insulation and coating cannot be underestimated. This is because it cannot be detected by conventional visual examination and in most cases traditional nondestructive testing systems.

Basically, metal especially carbon and low alloy steel under thermal insulation does not corrode itself since it is covered with the insulation. However corrosion can happen and initiate because of water ingression from external or internal sources within free supply of oxygen. The role of insulation itself may contribute to the corrosion attack. The insulation form an annular space where moisture can collect and form a barrier to the escape of water or water vapors, which can hastens the normal corrosion rate. With the presence of water contact and oxygen, the corrosion mechanism can accelerate [9].

1.2 Problem Statement

1.2.1 Problem Identification

CUI data are usually compiled from field data where personnel came to plant and do some inspections at equipments and make analysis for the corrosion rate of those equipments. The problems arise where personnel have to come to the plant every month to do inspection and collect the data. As a result **Table 1**shows the corrosion rate matrix - carbon steel external corrosion rate for corrosion under insulation

(CUI) in the marine, temperate, and also desert environments. However the data obtained in this table is grouped for wide range different of temperature, for an example, the corrosion rate for temperature 60 to 120 Celsius, and the corrosion rate is 0.13 mm/yr. This poses a big uncertainty especially for risk based inspection (RBI) analysis for equipments reliability. To ensure that data from **Table 1** can be used for (RBI), further experiments are required to find out the corrosion rate and the truth of this data.

In this study, the parameters of the CUI to occur were determined. The roles of each insulation materials, insulation designs, atmosphere, moisture entry, external environment, and operating temperature have been studied in order to formulate the problems for better understanding but only a few factors included in the investigation which is insulation materials, moisture entry, and operating temperature. This knowledge was used to design and develop a detailed drawing of corrosion test cell that can evaluate all these factors in standard laboratory condition.

1.2.2 Significance of the Project

This project concentrated on the investigation of corrosion rate for Corrosion under Insulation (CUI). Several experiments have been conducted to find out the corrosion rate by varying the temperature into smaller range of temperature. The data obtained from experiments may answer a question regarding an unreliable data from existence data either it can be used or not for Risk Based Inspection (RBI) analysis.

1.3 Objectives and Scope of Study

1.3.1 Objectives of Project

The objectives of the project are:

1. To determine the corrosion rate at marine environment for temperature 60 to 120 Celsius.

2. To determine the corrosion rate by varying the temperature into small gap of temperature; 60, 70, 80, and 90 Celsius.
3. To compare the corrosion rate between Linear Polarization Method (LPR) and Weight Loss.
4. To compare the results obtained from LPR and weight loss with the existence data in **Table 1**.

1.3.2 Scope of Study

The planning and designing of test involved defining goals and objectives, designing corrosion test, developing test protocol, engineering test, modifying test, results, evaluate the results and making conclusion. This scope of study is needed since corrosion test is an important tool for evaluating the performance of the materials used in scientific, industrial, engineering, consumer, and aesthetic applications. This project focused on investigation the corrosion rate by doing several experiments using corrosion test cell that follow standardization, engineering design process, corrosivity of specific environment and others. Meanwhile, the study of the CUI problem that covered effects of water, contaminants, operating temperature, insulation materials, equipments design, insulations design and materials were required for development of the test protocol.

CHAPTER 2
LITERATURE REVIEW

2.1 Corrosion under Insulation (CUI)

Corrosion under Insulation (CUI) has resulted to very high maintenance cost, loss of production time and equipment outages. This problem has been occurring since piping and equipment are insulated for energy conservation, process control and thermal protection. As mentioned earlier, intruding of water has contributed to the CUI problems. External water enters an insulated system mainly through breaks or damage in the insulation system. An additional of another factor is from internal source when the moisture in the air condenses on the metal surface below the insulation (sweating) as illustrated in **Figure 1**.

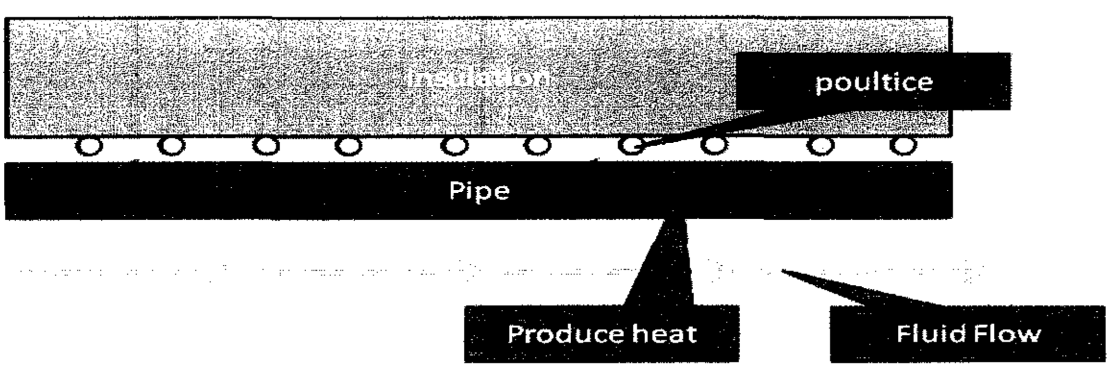


Figure 1: Illustration for Internal source mechanism

Basically, the insulation received from manufacturer is dry. Thus as long as the insulations are kept dry, corrosion problems will not happen. However the insulation it may contribute to CUI problem. The insulation can become wet while in storage and field erection. Furthermore, improper installation and maintenance of insulation may also simply caused corrosion under insulation. Painting and coating that has been applied as a barrier or protection on metal surface can also be damaged because of these imperfections [2]. Additionally, painting and coating itself contain defect that water can be leached and penetrated through.

Typically, insulation used has been based on Rockwool, Foam Glass or Calcium Silicate. These materials have different degrees of water uptake, but all required cladding with stainless steel or binding with special tape in order to keep in place, to seal from weather and prevent water penetration cracks and joins and reaching the surface. A typical insulation system in the susceptible temperature range consists of steel (base material), then a two-layer coating. Subsequently, there will be a layer of insulation material, possibly with (steam) tracing and covered by an insulation jacket such as aluminum, galvanized carbon steel and aluminized carbon steel.

2.2 Corrosion Mechanism

Corrosion under insulation is an electrochemical process that involves the transfer of electrically charged ions between the anode and cathode through the pore fluid of the insulation. Base metal usually carbon steel can also corrode by chemical means, such as an acid attack. The principles of electrochemical corrosion for a basic corrosion cell require the same components as the electrolytic cell, which must be established for corrosion to occur. The components that encompass the electrolytic cell include the anode, the cathode, and an electrolyte. In order for corrosion to occur, both anode and cathode must be connected in a manner that permits electron flow.

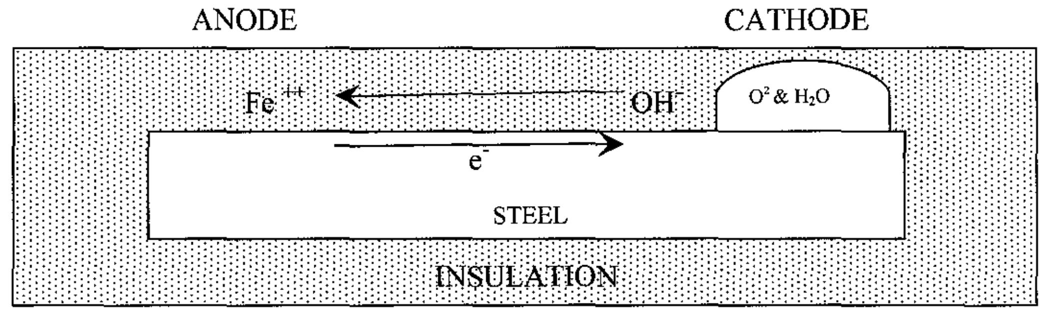


Figure 2: Corrosion Cell in Steel Covered by Insulation – Corrosion under Insulation Mechanism

The electrochemical process of corrosion involves oxidation at the anode and reduction at the cathode as in **Figure 2**. The site where the base metal corrodes is called the anode. Metallic iron (Fe) from the steel oxidized to produce ferrous ions and electrons are released according to Equation 2.2.1 [17].

$$\text{Anodic Reaction:} \qquad Fe \leftrightarrow Fe^{2+} + 2^{e-} \qquad (2.2.1)$$

In order to maintain equilibrium of charges, an electrochemical reduction occurs at the cathode. In an acidic medium, the reaction taking place at the cathode is the reduction of hydrogen ions to hydrogen. However, insulation is highly basic (pH 7 to 11) and usually has a sufficient supply of oxygen and water to form hydroxyl ions, as displayed in Equation 2.3.2

$$\text{Cathodic Reaction:} \qquad O^2 + 2H_2O + 4^{e-} \leftrightarrow 4(OH)^- \qquad (2.2.2)$$

The current drives both the anodic and cathodic reactions flows through a medium termed the electrolyte. The electrolyte conducts current primarily through ionic diffusion, and must have specific minimum ion content and a minimum water content to allow the flow of ions. In the case of corrosion under insulation, the pore water in insulations acts as the electrolyte. The electrolyte forming a corrosive environment may be any solutions, rain, or even moisture condensed from the air. It can range from fresh water to salt water to the strongest alkali or acid.

The combination of the anode and cathode processes results in the equations that transform the metallic iron (Fe) into hydroxides (rust)

$$Fe + 1/2O_2 + H_2O + 2e^- \leftrightarrow Fe^{2+} + 2(OH)^- + 2e^- \qquad (2.2.3)$$

Equation 2.3.3 simplifies to Equation 2.3.4 as follows

$$Fe + 1/2O_2 + H_2O \leftrightarrow Fe^{2+} + 2(OH)^- \qquad (2.2.4)$$

The Fe^{2+} cation combines with the hydroxyl ions $[(OH)^-]$ to form a fairly soluble ferrous hydroxide, Fe $(OH)_2$, which is rust that possesses a whitish appearance. The reaction is shown in Equation 2.3.5 with sufficient oxygen, Fe $(OH)_2$ is further oxidized to form $Fe(OH)_3$, which is the more common form of rust that has a reddish brown appearance.

$$Fe^{2+} + 2(OH)^{-} \leftrightarrow Fe(OH)_2 \qquad (2.2.5)$$

For the transformation of metallic iron to rust to occur, all three of the following conditions must take place. Iron must be available in a metallic state at the surface of steel during the anode process, oxygen and moisture must be available during cathode process and the electrical resistivity if insulation must be low to facilitate electron flow through the metal from anodic to cathode areas.

2.3 Factors Contributing to Corrosion Under Insulation

The susceptibility of equipment to Corrosion under Insulation depends on a number of factors. Some factors have a larger influence on CUI then others. Within the strategy presented all those factors discussed in detail in another section:

1. Water source
2. Operating Temperature
3. Equipment shape: line size, and nozzle attachment
4. Insulation accessory material
5. Coating status
6. Insulation type
7. External environment
8. Cladding and insulation condition
9. Internal corrosion

2.3.1 Water Source

The two primary sources involved in CUI are infiltration from external sources and condensation. Water infiltrates from external source such as rainfall, steam discharge, spray fire sprinklers, or drift from cooling towers. External water enters an insulated system through breaks in the weatherproofing. Condensation occurs when temperature of the metal surface is lower than the atmospheric dew point and cause poultice trap in between metal and insulation.

2.3.2 Operating Temperature

Service temperature is an important factor affecting CUI. Higher temperatures make water more corrosives, and paint and caulking will fail prematurely. Higher temperature tends to increase the corrosion rate and reduce the service life of protective coating, mastics, and sealant meanwhile higher temperature also reduces the time water is in contact with the carbon steel. Based on an experiment, shown that carbon steel operating in the temperature range -4^{0}C to 150^{0}C is at the greatest risk from CUI.

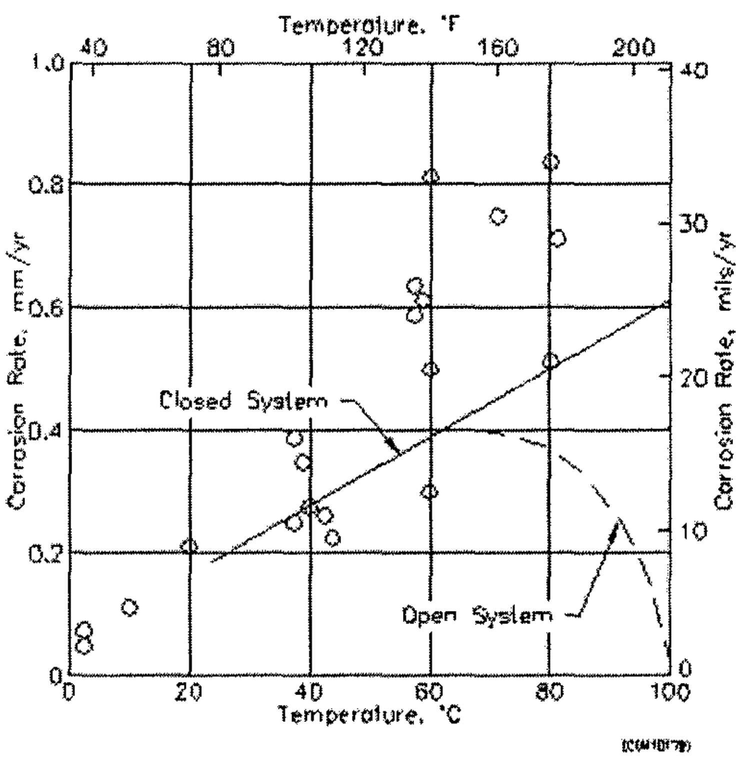


Figure 3: Comparison of Actual Plant CUI corrosion Rates measurements (Open Data Points Shown is for Plant CUI) with laboratory Corrosion Data Obtained in Open and Close Systems

Figure above shows the effect of the temperature towards the corrosion rate. Both closed system and open system still being affected by the increasing of the temperature [16]

2.3.3 Equipment Shape: Line Size, and Nozzle Attachment

The design of equipment and piping attachment is an important part of insulation system design [11]. The shape, geometry, and orientation of attachments can allow moisture or rainwater to penetrate the insulation and to concentrate at the attachment point. Failure to employ joints at the required locations in the insulation can lead to its uncontrolled movement. As a result, weather barriers and vapor barriers break down. This can allow migration of water into the insulation and lead to corrosion.

2.3.4 Insulation Accessory Material

Insulation accessory materials also provide weatherproofing and seal projections through insulation system. These accessories are used to fabricate insulation materials into shapes that fit pipe and equipment. Failed to do so may cause failure of coating to protect equipments.

2.3.5 Coating Status

A protective coating's function is to prevent corrosive service environments from contacting the underlying steel substrate and initiating corrosion. To accomplish this function, a coating must have several properties essential to maintaining a proper barrier to the environment. Some of the more important properties are: water permeability resistance, weathering resistance, ease of application, sunlight resistance, good adhesion, and abrasion resistance.

2.3.6 Influence of Chloride in Insulation

The value for the alkaline solution runs from pH 7 to 11, carbon and alloy steels are normally passive in alkaline environments and have minimal corrosion rates. However, chloride ions (Cl^-) tend to break down this passivity locally and initiate pitting corrosion in the acidic solution. As pH drops below 4, corrosion climbs dramatically although without presence of oxygen. The source of the chloride come either from the insulation material itself or from external sources such as rain, coastal fog, wash water, fire and deluge system testing.

2.3.7 External Environment

Corrosion rates for the service environment have been specified by American Petroleum Institute (API) 581 where temperature application and climate condition (rain fall) results into selection of a corrosion rate [8] (refer **Table 1**). Corrosion under insulation (CUI) results from the collection of water in the vapor space (or annular space) between the insulation and the metal surface. Sources of water may include rain, water leaks, condensation, cooling water tower drift, deluge systems, and stream tracing leaks. CUI causes wall loss in the form of localized corrosion. CUI generally occur in the temperature range between -12°C and 120 °C, with temperature range of 50 °C to 90 °C being the most severe environment [8].

Table 1: Corrosion rate default matrix – carbon steel External corrosion rate for Corrosion under insulation (CUI)

Operating Temperature °C	Driver (mm/yr)		
	Marine	Temperate	Arid/Desert
-12 or less	0	0	0
-12 to 16	0.13	0.08	0.03
17 to 50	0.05	0.03	0
51 to 93	0.13	0.05	0.03
94 to 120	0.03	0	0
>120	0	0	0

Table 1 shows the corrosion default matrix for carbon steel external corrosion rate for CUI that being converted from Table N-3in API 581 [8] (see **Appendix B**).

2.4 Planning and Design of Test

Corrosion test are used to examine the performance of materials, evaluate alternate materials, develop strategies for protection of materials, and determine the corrosivity of specific environments. Corrosion test planning and design typically involves the following five steps:

1. Define goals and objectives
2. Design corrosion test
3. Develop test protocol
4. Engineer test
5. Modify test
6. Results
7. Evaluate the results

These steps are affected by the nature of the corrosion process, the types of data acquired, the analytical resources available, and the statistical treatments to be applied, and the outcomes sought. Preliminary or early data can help determine whether the fifth step, modification of the test design will be needed. Goal and objectives define the test purpose and what is to be achieved. Meanwhile test protocol develops a set of reliable and reproducible measurement that achieve the goals and objectives of the test. The test protocol may simply be a guide or 'road map' to the raw or un-interpreted measurements defining methods and standards.

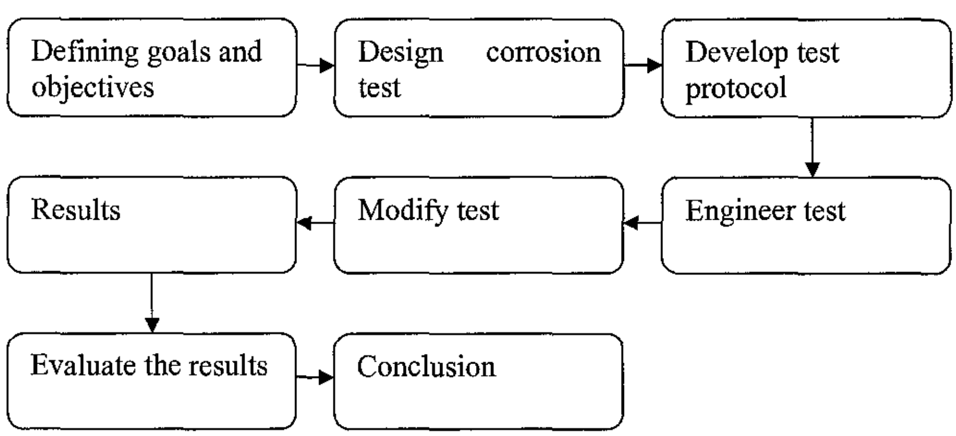
The objectives for performing a corrosion test should be identified during the initial phase of designing the testing procedure. The test conditions including specimen size, test environment versus service environment, geometry, sample preparation, temperature, flow velocity, potential and type of corrosion test (general, crevice, pitting resistance, galvanic, stress related, dealloying, etc) should be considered.

CHAPTER 3
METHODOLOGY AND PROJECT WORK

3.1 Procedure Identification

Literature review such as information regarding Corrosion under Insulation (CUI), corrosion test and standard, corrosion mechanism, and corrosion standard procedure were collected through corrosion journal, textbooks, magazines, reference manuals, newspapers, and articles. Moreover, the internet provides access to numerous and references were selected based on objectives, scope of works and relevancy of project. This is important to get the best solution and quality of corrosion test results.

3.1.1 Flow Chart of Procedure



3.2 Procedure before testing

Before implementing any corrosion test, care must be taken when selecting the corrosive media and preparing the test specimen [6]. Accelerating tests often represent the worst-case scenario, requiring a very aggressive corroding factor. The onset of corrosion may seriously accelerate damage in an entirely unpredictable manner. Caution must be exercised to make certain the corrosion mechanism is not altered. Consequently, most accelerated tests should not be used to predict life or corrosion rates. These tests are typically qualitative, and the information obtained from them is best used to down-select the most appropriate materials for use in specific applications.

3.3 Method of accelerating corrosion testing

Testing does not have to correlate exactly to the service environment as long as the corrosion mechanism remains the same. However, the results of accelerated testing should correlate to results from more reliable sources, e.g.; service experience and field testing. The method of accelerating corrosion testing will depend upon material the material examined, the environment and the type of corrosion mechanism. Several common methods for acceleration in this study include increasing:

- Temperature (The most common and greatest accelerating factor)
- Acidic
- The amount of NO2, chloride for atmospheric tests
- Relative humidity for atmospheric tests

Additionally for aqueous corrosion, the corroding electrolyte and the ionic conductivity help determine the rate corrosion attack. Even when accelerated, corrosion test can be inherently slow; hence, testers must exercise control of these variables.

3.4 Corrosion under Insulation Test Cell

The schematic diagram of the CUI test cell designed for laboratory simulation for CUI on a pipe section for initial tests is detailed in **Figure 5**. This initial cell consisted of five ring specimens, which were separated by Teflon™ spacers. The testing section was fabricated by placing two blind flanged pipe sections on both ends. Three pipe clamps were used to hold the cell set-up together. The test temperature at the ring surfaces was achieved via an immersion heater incorporated to the inside of the pipe section, which was filled with thermal conductive silicone oil (SF97-50 silicone dielectric fluid). A block of thermal insulation placed above the testing section provided the annular space to retain test environment. The insulation used was a water-resistant molded Pearlite (Temperlite™).

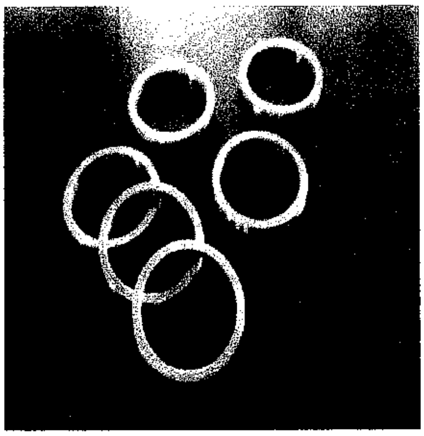


Figure 4: Ring specimens

One half of the outer surfaces of the ring specimens were exposed to the test environment during the testing. The rings were used for test electrodes in two separate electrochemical cells (**Figure 4**).

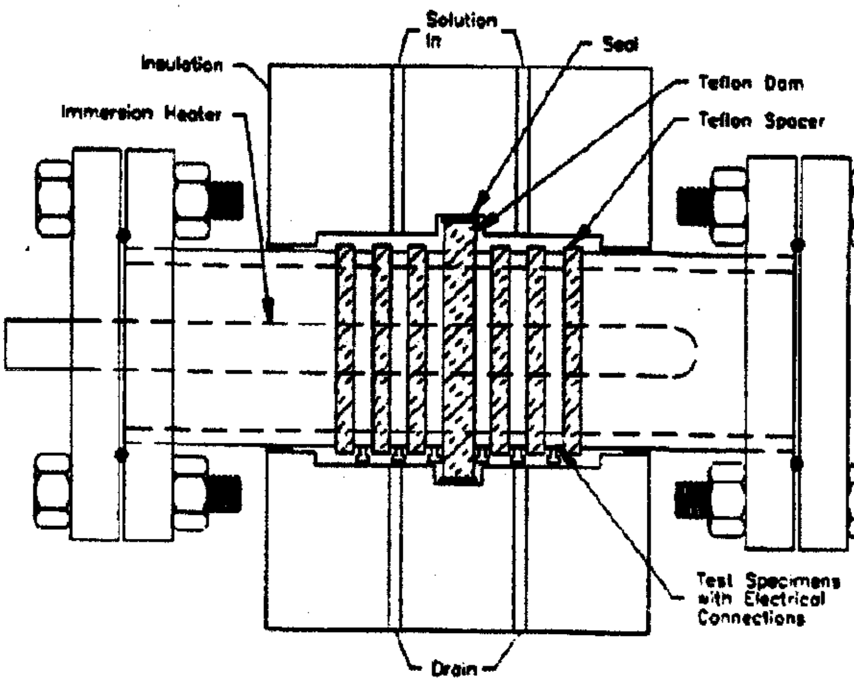


Figure 5: Detailed schematic

The center ring was used as a common reference electrode (RE) for the cells. The rings on either side of the RE were used as the working electrodes of the two cells. The outer most rings served as the counter electrodes. This five-ring cell set-up was later modified to a six-ring cell set-up as shown in **Figure 5**. In this case, the two electrochemical cells were separated by placing a Teflon dam (ring of 3.0 inch (7.6 cm) O.D.) at the center. In both electrochemical cells, the center ring was the WE while the other two rings were the CE and the RE (see **Figure 9**).

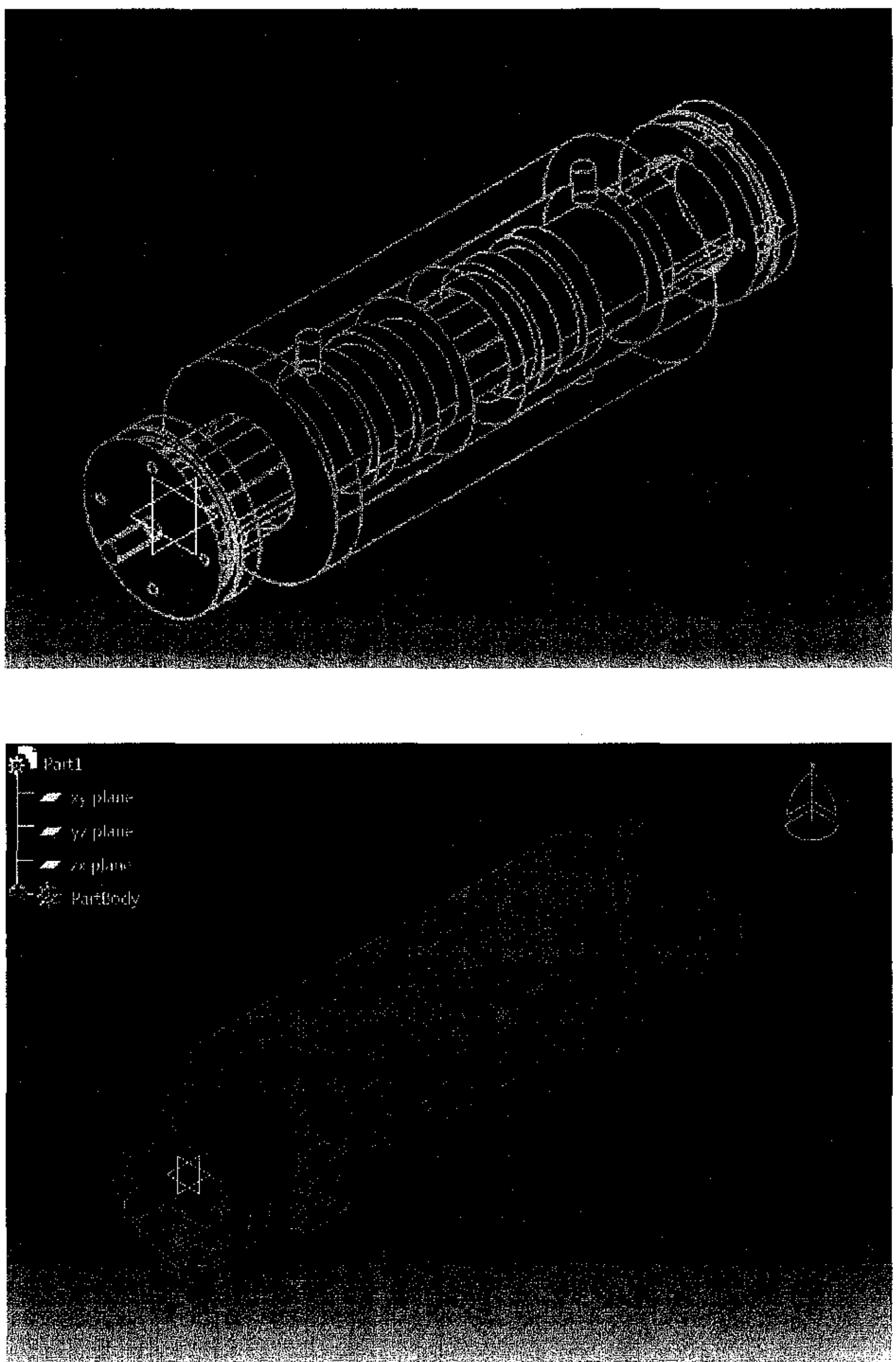


Figure 6: 3D Model of CUI Test Cell

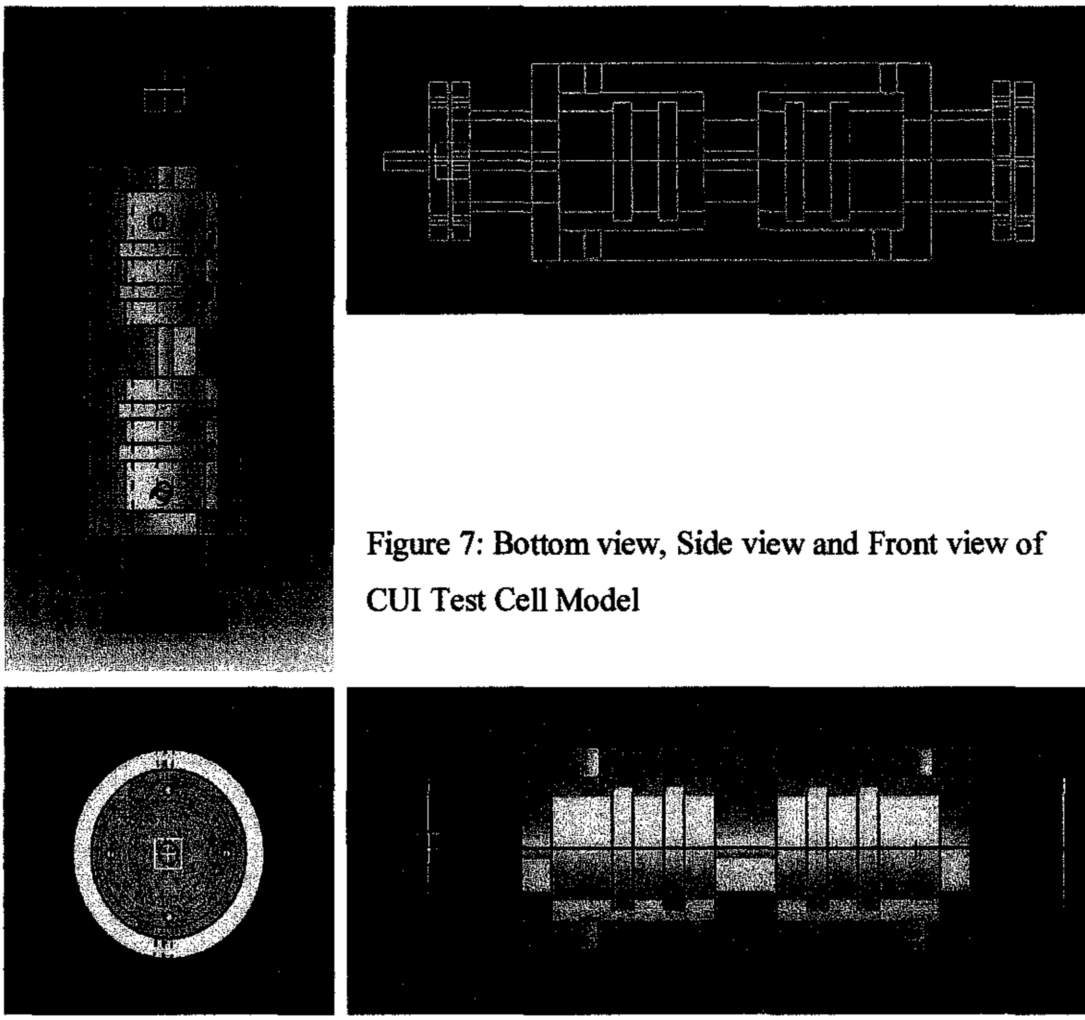


Figure 7: Bottom view, Side view and Front view of CUI Test Cell Model

3.4.1 Fabrication

A complete set of CUI test cell is fabricated by manufacturer because such fabrication is quite complicated and time consuming to be done and it take approximately three month to be completed. **Figure 8** shows the major dimension and components of the CUI test cell. All those components are separated from each other where assembling process is required to make it a complete set as in **Figure 9.** For the safety purposes, two peoples required to assemble it because of the heavy components. The dimensions shows below are in Inches unit.

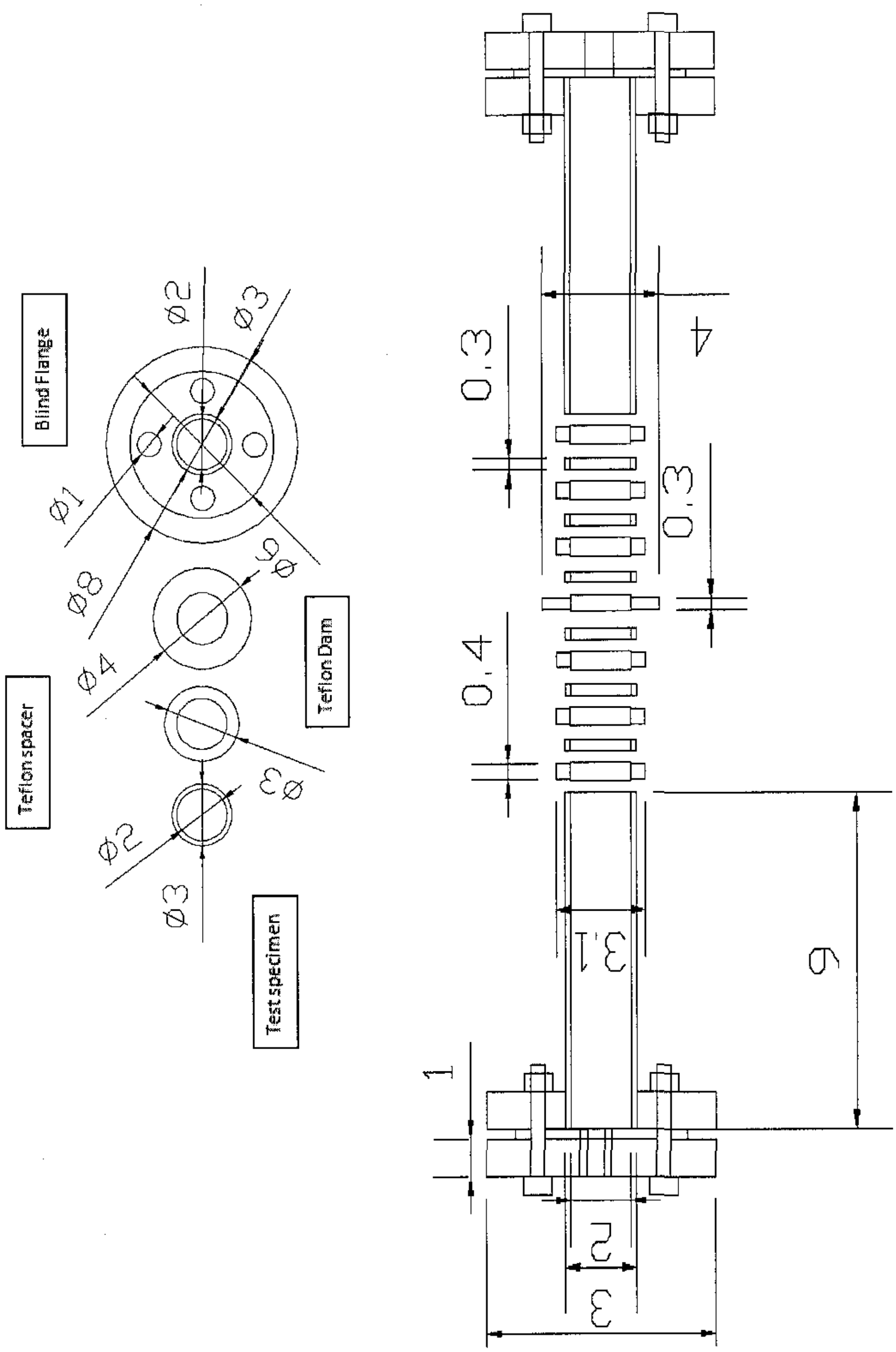
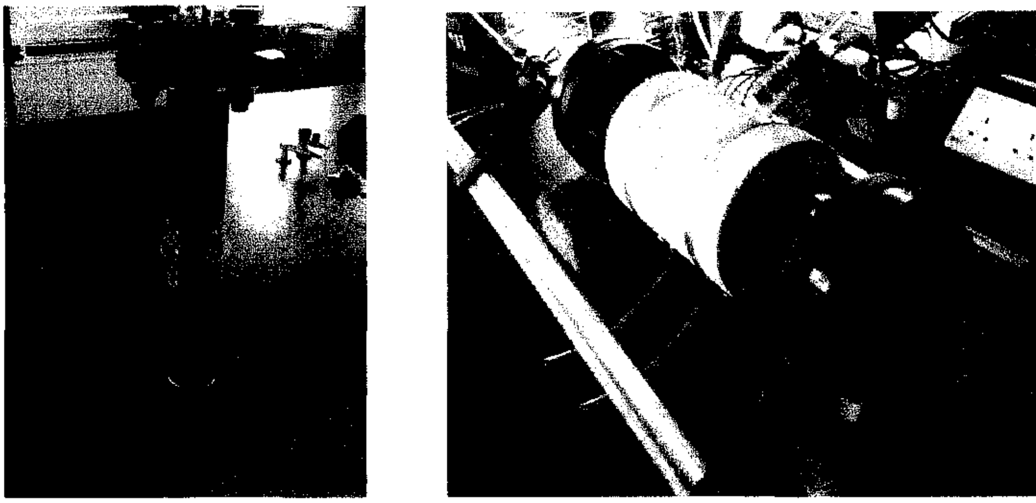


Figure 8: Two Dimensional drawing showing the major dimensions of CUI test cell *(All units in inches)*



(a) (b)

Figure 9: Corrosion under Insulation Test Cell. Picture (a) shows two separate blind flanges being assemble together, where in between of the blind flanges are Teflon spacers and ring specimens. Picture (b) shows CUI test cell with insulation.

3.5 Measurements

Measurement of current or current density is the most common output of electrochemical corrosion tests. The relationship between the measured current and the corrosion rate or mechanism depends to some degree on the technique used to obtain the current. The type of data obtained and the format by which the information is displayed depend on the test. Some test display voltage versus current, others display voltage versus the logarithm of the current, others display information about impedance (voltage divided by the current), and others examine fluctuations in the current around some average value. These different types of data have different uses and may require additional types of data or analysis programs to translate the data into usable information.

3.5.1 Corrosion Rate from Mass Loss

The most common method for estimating the corrosion rate is from the mass loss of a metal specimen of known dimensions immersed in a fluid for a known amount of time. The weight of the specimen is obtained before and after the exposure. The corrosion rate is obtained by dividing by the exposed area, the time, and the density. The corrosion rate expressed as millimeters per year can be calculated by equation

$$\frac{mm}{y} = \frac{mass\ loss \times 87.6}{(area)(time)(metal\ density)} \tag{3.5.1}$$

Where test specimen mass loss is expressed in mg, area in cm^2 of test specimen surface exposed, time in hours exposed, and the metal density in g/cm^3

$$\frac{mils}{y} = \frac{mass\ loss \times 534.57}{(area)(time)(metal\ density)} \tag{3.5.2}$$

Where test specimen mass loss is expressed in mg, area in in^2 of test specimen surface exposed, time in hours exposed, and the metal density in g/cm^3

3.5.2 Linear Polarization Resistance Method

This steady-state method defines the polarisation resistance of a material as the slope of the potential – current density (ΔE / Δi) curves at the free corrosion potential [3], yielding the polarization resistance, R_p.

The schematic of the linear polarization curve is shown in the subsequent figure.

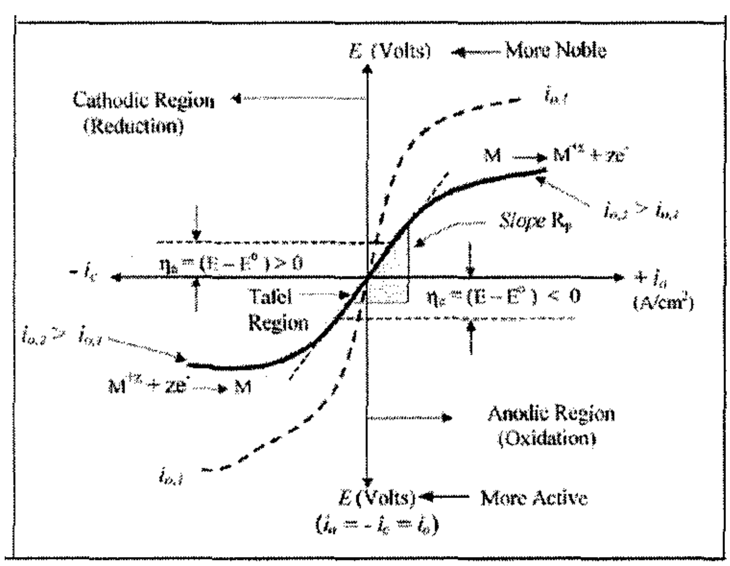


Figure 10: Schematic Linear Polarization Curve

The linear polarization is confined to a small magnitude of overpotentials of ήa and ήc, respectively, using linear coordinates. The technique allows the determination of i_{corr} using a potential range of $\pm$ 10 mV from the E_{corr} [11]. R_p can be calculated from:

3.6 Test Matrix

The subsequent test matrix will be applied:

Table 2: Parameters

Parameter	Value
Steel type	BS 970 (080A15)
Concentration of NaCl Solution	0.5g of NaCl to 5L of reagent water
pH	6
Atmosphere Temperature (°C)	24
Temperature (°C)	60, 70, 80,90, 100, 110, 120
Metering Pump speed	30 spm for 50 stroke power
Heating Solution	Cook Oil
Insulation Type	Pearlite, glass form
Surface Roughness	600 grit finish
Measurement Technique	Linear Polarization Resistance (LPR), Weight Loss

The estimated corrosion rates for carbon and alloy steel shown in **Table 3** are not accurate because of the temperature different are high [8].

Table 3: Corrosion rate default matrix – carbon steel External corrosion rate for Corrosion under insulation (CUI)

Operating Temperature °C	Driver (mm/yr)		
	Marine	Temperate	Arid/Desert
-12 or less	0	0	0
-12 to 16	0.13	0.08	0.03
17 to 50	0.05	0.03	0
51 to 93	0.13	0.05	0.03
94 to 120	0.03	0	0
>120	0	0	0

The test matrices shown below will be use in this experiment to gather the results for evaluation purposes. Temperature range between -5 to 60 Celsius and also 120 to 150 Celsius shows low corrosion rate compare to the temperature range 60 to 120 Celsius. Sheldon W. Dean [9] stressed that for carbon steel the temperature range between 60 to 120 are the higher corrosion rate occurred.

These test matrices are divided onto three days because the guide provides information on CUI in a relatively short time (approximately 72 hours) as well as providing a means of assessing variation of corrosion rate with time and environmental conditions [13]. From the Sheldon W. Dean theory [9] the graph for this experiment can be assume to be the corrosion rate proportional to the temperature until the temperature get over 120 Celsius.

CHAPTER 4
RESULTS & DISCUSSION

4.1 Introduction

The objective to obtain results from the experiments has been succeeding. Because of the time constraint, only four results from experiments at temperature 60 °C, 70 °C, 80 °C, and 90 °C for both LPR and Weight lost were obtained (see **Table 4** and **Table 5**). The main factors that contributed CUI to occur are the ingression of water and temperature, which is salt water with pH 6 for these experiments. As **Table 3** shown above, the highest corrosion rate to occur is in between 60 °C to 120 °C , it is difficult to use that data for the reliability analysis because of the big range of temperature. Therefore, this experiment comes out with more details corrosion rate at smaller range of temperature (see **Table 6**), which is the data more relevant to use for reliability analysis.

4.2 LPR Test Result

Table 4: LPR test result for temperature 60, 70, 80, 90°C (mm/year)

	Corrosion Rate (mm/year) for experiments:			
Time (Minutes)	60 °C	70 °C	80 °C	90 °C
0	0.15	0.18	0.12	0.11
10	0.14	0.18	0.20	0.10
20	0.19	0.18	0.18	0.12
30	0.18	0.16	0.23	0.12
40	0.18	0.18	0.18	0.11
50	0.17	0.17	0.16	0.12
60	0.17	0.17	0.14	0.12
70	0.17	0.17	0.16	0.12
80	0.17	0.18	0.15	0.12
90	0.17	0.17	0.16	0.12
100	0.17	0.17	0.16	0.12
110	0.17	0.16	0.14	0.13
120	0.17	0.17	0.15	0.12
130	0.16	0.17	0.12	0.12
140	0.17	0.17	0.12	0.12
150	0.17	0.17	0.15	0.12
160	0.17	0.16	0.14	0.13
170	0.17	0.16	0.13	0.14
180	0.17	0.16	0.14	0.13

*This result for only three (3) hours time frame only, full result (72 hours) can be found in the **Appendix A**.*

The corrosion rate at temperatures 60, 70, 80 and 90 °C can be conclude that the corrosion rate is in between 0.10 to 0.20 mm/yr as shown in **Table 4.**

4.2.1 Corrosion rate

The instantaneous corrosion rate versus time produced from LPR data obtained in CUI simulations are given in **Figure 11, 12, 13** and **14** for different temperatures.

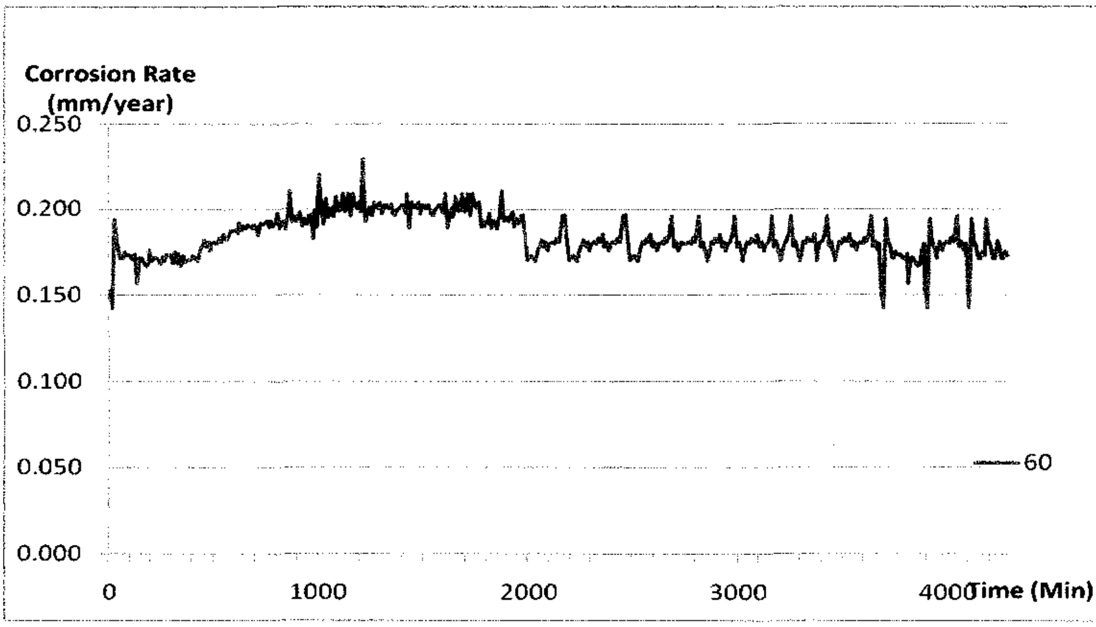


Figure 11: Graph of corrosion rate (mm/yr) vs. time (min) at temperature 60 °C

For corrosion rate versus time at temperature 60 °C as shown in **Figure 11**, the highest corrosion rate is at 0.23 mm/yr while the lowest is 0.14 mm/yr. The average of the corrosion rate at temperature 60 °C is 0.18 mm/yr.

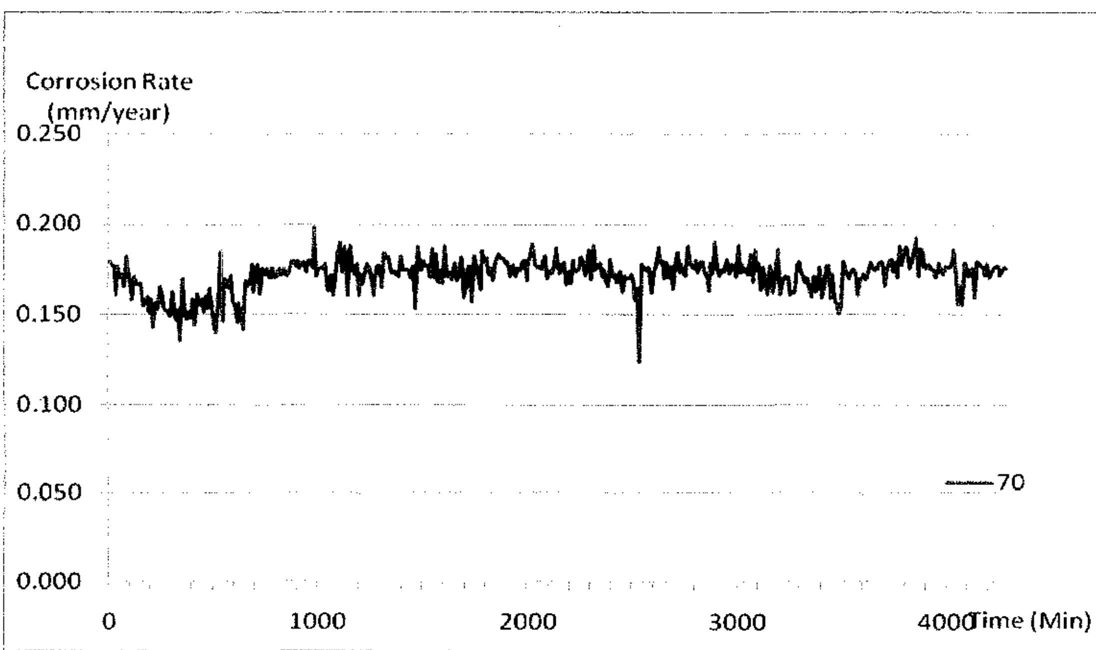


Figure 12: Graph of corrosion rate (mm/yr) vs. time (min) at temperature 70 °C

In **Figure 12**, the corrosion rate versus time at temperature 70 °C, the highest corrosion rate is at 0.20 mm/yr while the lowest is 0.12 mm/yr. The average of the corrosion rate at temperature 70 °C is 0.17 mm/yr.

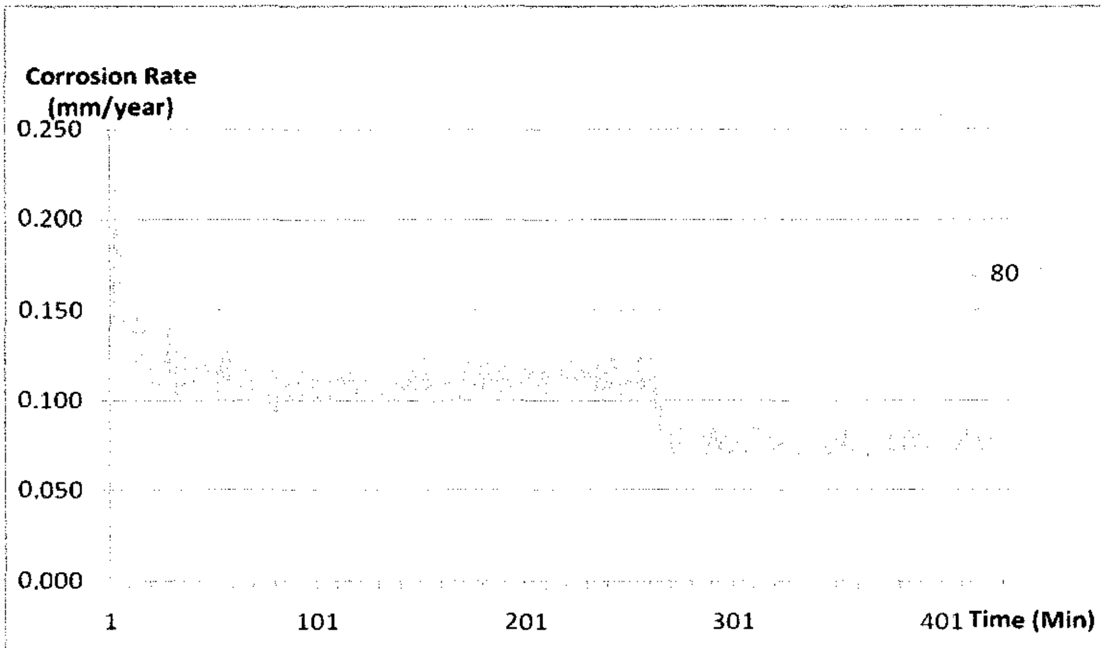


Figure 13: Graph of corrosion rate (mm/yr) vs. time (min) at temperature 80 °C

For corrosion rate versus time at temperature 80 °C as shown in **Figure 13**, the highest and lower corrosion rate are 0.23and 0.07 mm/yr, respectively. The average of the corrosion rate at temperature 70 °C is 0.01 mm/yr.

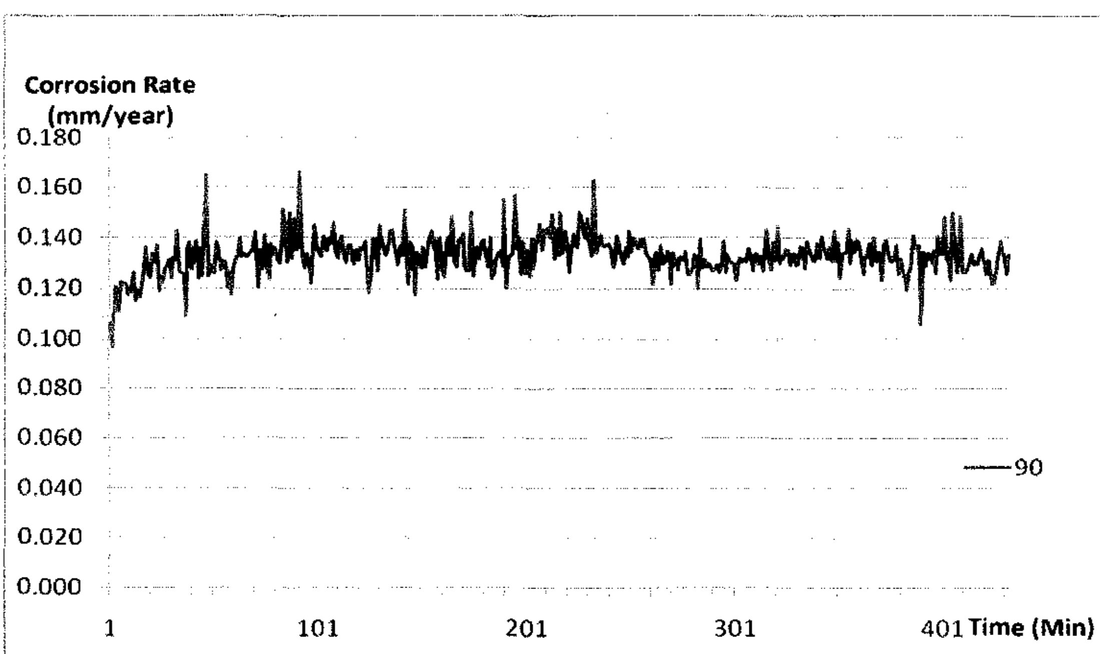


Figure 14: Graph of corrosion rate (mm/yr) vs. time (min) at temperature 90 °C

For corrosion rate versus time at temperature 90 °C as shown in **Figure 14**, the highest corrosion rate is at 0. 17 mm/yr while the lowest is 0. 10 mm/yr. The average of the corrosion rate at temperature 90 °C is 0.13 mm/yr.

4.2.2 Corrosion rate comparison

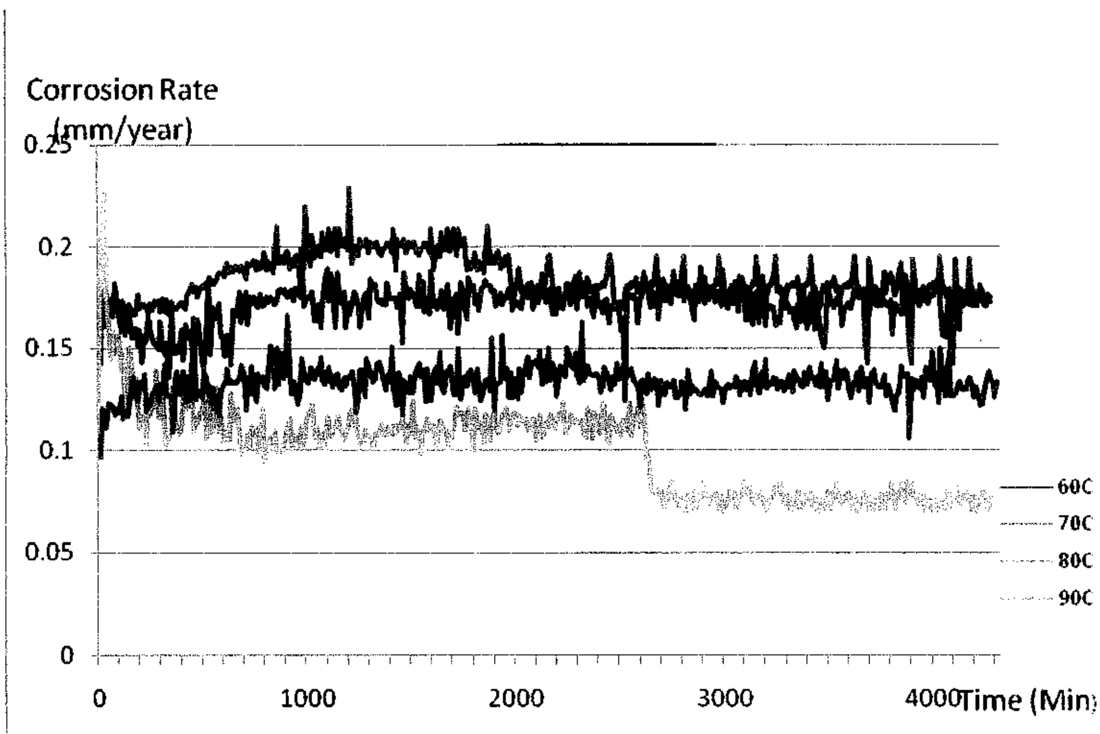


Figure 15: Graph of corrosion rate (mm/yr) vs. time (min) for LPR test result at temperatures 60, 70, 80 90°C

It should be noted that the actual values of corrosion rate determined by the LPR techniques may vary from the average corrosion rates determined by the mass loss of the specimens. However, as shown in **Figure 15**, the corrosion rates determined from LPR techniques may provide valuable information on the changes in corrosion rate with time and the influence of different temperatures and their cumulative effect on the corrosion rate during the course of particular CUI experiments. This type of data can also be used to evaluate the role of changing exposure condition on the severity of CUI.

Table 5: Average corrosion rate for LPR after 72 hours

Temperature (C)	Corrosion rate (mm/yr)
60	0.19
70	0.17
80	0.11
90	0.13

4.3 Weight Loss Test Result

Table 6: Table of weight loss test result at experiments 60, 70, 80, 90 °C

Experiment	Sample	Before (g)	After (g)	Total Loss (g)	in mg	mm/yr	mils/yr
60 °C	1	37.555	37.546	0.009	9	0.12	4.85
	2	37.679	37.663	0.016	16	0.22	8.63
	3	37.156	37.146	0.01	10	0.14	5.39
70 °C	1	37.456	37.437	0.019	19	0.26	10.24
	2	37.647	37.636	0.011	11	0.15	5.93
	3	37.652	37.642	0.01	10	0.14	5.39
80 °C	1	36.879	36.87	0.009	9	0.12	4.85
	2	37.475	37.466	0.009	9	0.12	4.85
	3	37.683	37.671	0.012	12	0.16	6.47
90 °C	1	37.288	37.276	0.012	12	0.16	6.47
	2	37.456	37.446	0.01	10	0.14	5.39
	3	36.642	36.631	0.011	11	0.15	5.93

By using the formula from **Equations 3.5.1** and **3.5.2** for weight loss in mm/yr and mils/yr, respectively, the corrosion rate may be obtained easily as shown in **Table 5** at different temperatures. Where the total area exposed to the corrosion is 11.7cm^2, time hours constant is 72 hours and the density is 7.5869g/cm^3. By getting the total loss of the samples before and after experiments and convert the unit from grams to milligrams, put in the values in the **Equations 3.5.1** and **3.5.2** to get the corrosion rate.

4.3.1 Corrosion rate comparison

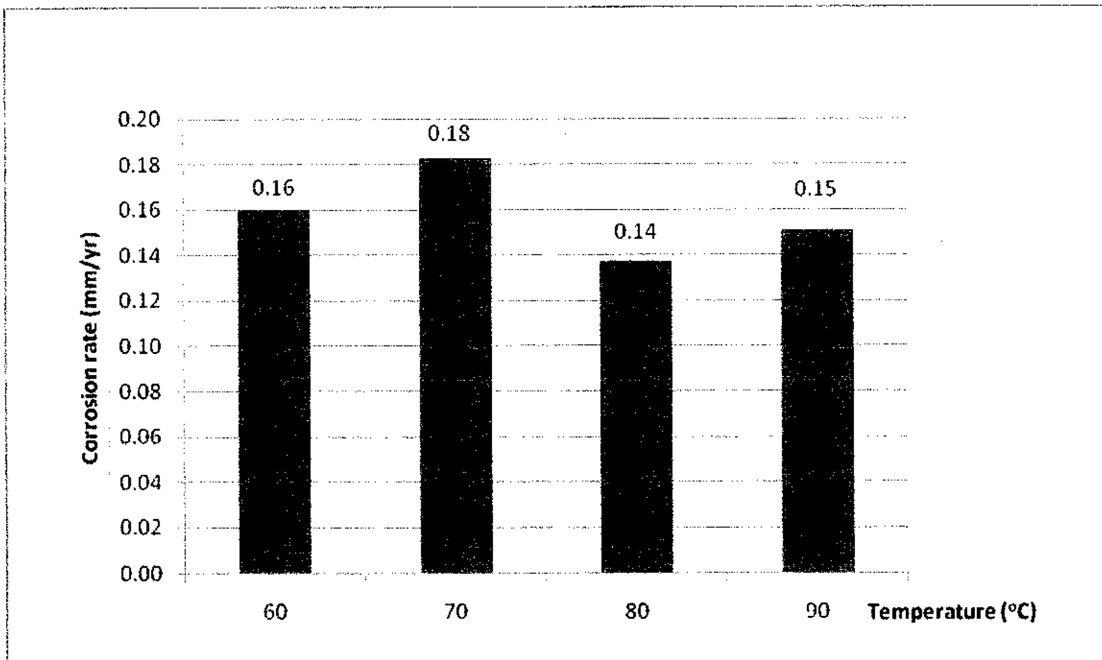


Figure 16: Graph of corrosion rate (mm/yr) vs. time (min) for weight loss test result at temperatures 60, 70, 80 90°C

The trend from graph **Figure 16** shows there is not much different for the corrosion rate at different temperature for the weight loss experiments. It concludes that the corrosion rates at range temperature 60 °C to 90 °C are almost the same. From **Figure 14**, the highest corrosion rate occurred at temperature 70 °C while the lowest corrosion rate at 80 °C. The corrosion rate tend to reduce from temperature 70 °C to 80 °C from 0.1828 mm/yr (7.1916 mils/yr) to 0.1371 mm/yr (5.3937 mils/yr), respectively. It is because, when the temperature increase the heat produce also increase, therefore more oxygen being consumed to produce the heat. The lack of oxygen inside the insulation may result the corrosion rate to decrease. Other reason is the solution evaporates before it touches the metal surfaces which mean the metal surfaces are in dry condition where the corrosion very slow to occurs.

4.4 Overall Corrosion Rate

Table 7: Overall corrosion rate for LPR, Weight Loss and API 581

Temperature (°C)	Corrosion Rate (mm/year)		
	LPR	Weight Loss	API 581
60	0.19	0.16	0.13
70	0.17	0.18	0.13
80	0.11	0.14	0.13
90	0.13	0.15	0.13

Table 7 shows the overall corrosion rate for both LPR and weight loss techniques. To make it clear, a graph of comparison being constructed for LPR and weight loss techniques as shown in the **Figure 17**.

4.4.1 Overall Corrosion rate comparison

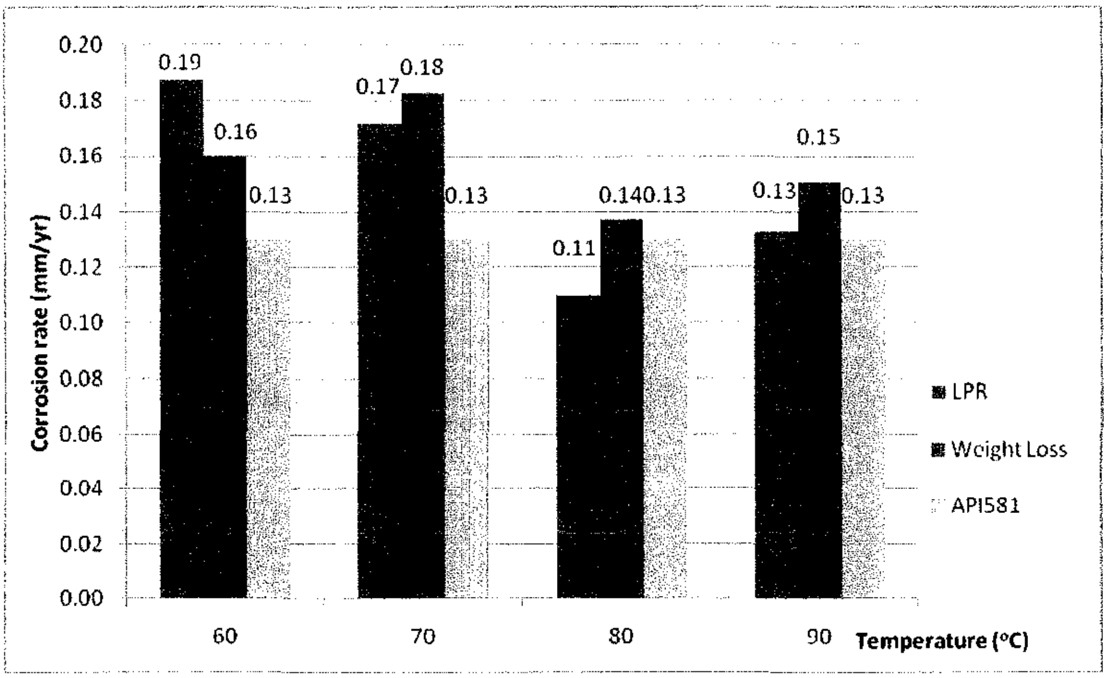


Figure 17: Graph of corrosion rate (mm/yr) vs. temperature (°C) for LPR, weight loss and API 581test result at temperatures 60, 70, 80 90°C

The corrosion rate versus temperatures for LPR and weight loss as shown in **Figure 17** may explain that, there is not much different in results between those two techniques to determine the corrosion rate. The corrosion rate for weight loss at temperatures 70, 80, and 90°C are highest compare to LPR. However at temperature 60 °C the corrosion rate at the other way round, the corrosion rate for LPR much higher than weight loss. The corrosion rate for LPR and weight loss at temperature 60 and 70 are averagely in the range of 0.18 mm/yr and 0.17 mm/yr, respectively. While for temperature 80 and 90 are 0.12 mm/yr and 0.14, respectively. Results, LPR and weight loss are considered as good results because the differences results with API 581 are much likely close each order. Therefore, **Table 1** is approved and can be considered to use it in risk based inspection (RBI) for further analysis process.

CHAPTER 5
CONCLUSION & RECOMMENDATION

5.1 Conclusion

The result obtained from two types of experiments, which are Linear Polarization Resistance (LPR) and Weight Loss at temperatures 60, 70, 80, and 90°C. Both results show the similarity of the corrosion rate, where can be concluded that the corrosion rate is in the range of 0.10 to 0.20 mm/yr. It is shown that the corrosion rates are approximately in the range of the estimated corrosion rate table. The conclusion from this experiment may be described, as increasing the temperature may increase the corrosion rate. But towards to the certain level of temperature, the corrosion rate obviously decreasing, the reason of that is as the temperature increase the heat produced also increase. The more heat produced the more oxygen being consumed, therefore less oxygen available inside the insulation. Lack of oxygen may cause the corrosion rate to reduce. Other reason is the solution evaporates before it touches the metal surfaces which mean the metal surfaces are in dry condition where the corrosion very slow to occurs.

(a) (a)

Figure 18: (a) Ring specimens before experiment, (b) Ring specimens after experiment

Higher temperatures also tend to accelerate the corrosion process beneath insulation. The degree of corrosion rate of closed systems is similar to the open system but increase linearly because of oxygen held in the closed system. Generally, CUI occurs in the temperature ranges between -5 °C and +150 °C. the temperature range of +60 °C to 120 °C being the most severe environment and high CUI risks

Area that are normally coated at high temperature paints system which tends to remain intact all of the time the structure operates at high temperature, but can crack and flake when subjected to temperature cycling and thus ceases to give protection at the lower temperature where it is needed. Additionally, a good coating system should last at least 8 years and with a sound maintenance programme, the coating system will provide longer protection against CUI

5.2 Recommendation

5.2.1 Study on Corrosion under Insulation prevention

Scientist at Elisha Technology Co [15], have developed a product, in a non flammable gel form to protect metals under insulation at high process temperature called **SmartGel 100.** The preliminary laboratory results are very positive with very good corrosion prevention performance.

SmartGel 100 reduced the corrosion rate approximately by the factor of ten and was effective in different practical applications [15]. This product has been designed to be applied with a minimum amount of surface preparation and flexible in delivery. The prevention techniques will be continuing by future project as part of final year project.

5.2.2 Investigate the corrosion rate on different type of steels

For other future recommendation, further analysis can be done on the different type of metals for better understanding on corrosion under insulation problem. Gathering difference corrosion rate by varying the type or metals may help to get solid results. Comparison can be made to find out which metals are low in corrosion rate and more suitable to use in industry.

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APPENDICES

Appendix A: Corrosion Rate (mm/year) at pH 6

	Appendix A: Corrosion Rate (mm/year) at pH 6			
	Temperature (Celcius)			
	60	70	80	90
Time (Minutes)				
0	0.153	0.179	0.124	0.106
10	0.143	0.178	0.205	0.097
20	0.194	0.177	0.181	0.121
30	0.181	0.161	0.225	0.119
40	0.178	0.176	0.176	0.111
50	0.171	0.170	0.161	0.123
60	0.171	0.172	0.145	0.122
70	0.175	0.166	0.158	0.122
80	0.173	0.182	0.148	0.118
90	0.173	0.172	0.156	0.120
100	0.171	0.166	0.156	0.119
110	0.171	0.158	0.139	0.127
120	0.174	0.171	0.147	0.115
130	0.156	0.167	0.120	0.119
140	0.171	0.167	0.123	0.117
150	0.172	0.167	0.150	0.123
160	0.169	0.155	0.142	0.130
170	0.167	0.157	0.134	0.136
180	0.167	0.160	0.135	0.126
190	0.177	0.151	0.119	0.124
200	0.170	0.159	0.111	0.134
210	0.172	0.143	0.116	0.130
220	0.172	0.156	0.115	0.137
230	0.170	0.153	0.102	0.119
240	0.168	0.166	0.121	0.125
250	0.172	0.160	0.117	0.122
260	0.169	0.154	0.123	0.128
270	0.173	0.152	0.121	0.129
280	0.173	0.152	0.139	0.131
290	0.173	0.149	0.116	0.124

300	0.169	0.163	0.126	0.132
310	0.175	0.150	0.129	0.132
320	0.168	0.147	0.103	0.143
330	0.174	0.153	0.103	0.127
340	0.167	0.136	0.107	0.126
350	0.173	0.170	0.110	0.126
360	0.169	0.151	0.131	0.109
370	0.170	0.147	0.112	0.136
380	0.170	0.151	0.112	0.138
390	0.172	0.148	0.107	0.128
400	0.173	0.159	0.112	0.135
410	0.171	0.144	0.127	0.139
420	0.170	0.161	0.126	0.124
430	0.176	0.155	0.120	0.136
440	0.179	0.159	0.131	0.125
450	0.182	0.151	0.125	0.145
460	0.178	0.161	0.109	0.165
470	0.180	0.154	0.116	0.125
480	0.175	0.164	0.113	0.129
490	0.179	0.155	0.118	0.129
500	0.181	0.144	0.121	0.126
510	0.180	0.140	0.123	0.138
520	0.183	0.158	0.106	0.135
530	0.181	0.185	0.132	0.127
540	0.185	0.146	0.108	0.131
550	0.183	0.170	0.109	0.130
560	0.182	0.168	0.112	0.120
570	0.184	0.165	0.130	0.127
580	0.187	0.172	0.108	0.118
590	0.187	0.157	0.116	0.128
600	0.188	0.154	0.104	0.131
610	0.186	0.146	0.105	0.133
620	0.192	0.156	0.109	0.140
630	0.188	0.149	0.105	0.133
640	0.191	0.142	0.127	0.134
650	0.189	0.169	0.114	0.133
660	0.191	0.166	0.118	0.133
670	0.190	0.169	0.120	0.134
680	0.188	0.178	0.105	0.135
690	0.191	0.163	0.098	0.142

700	0.190	0.175	0.102	0.138
710	0.185	0.178	0.100	0.120
720	0.192	0.162	0.107	0.135
730	0.191	0.175	0.102	0.128
740	0.192	0.172	0.111	0.141
750	0.193	0.175	0.107	0.128
760	0.189	0.171	0.111	0.124
770	0.193	0.170	0.099	0.137
780	0.189	0.176	0.107	0.133
790	0.191	0.171	0.120	0.136
800	0.197	0.172	0.094	0.131
810	0.189	0.175	0.104	0.130
820	0.193	0.172	0.102	0.139
830	0.192	0.175	0.106	0.151
840	0.188	0.174	0.103	0.145
850	0.196	0.171	0.109	0.131
860	0.210	0.174	0.099	0.150
870	0.193	0.179	0.099	0.132
880	0.195	0.179	0.099	0.148
890	0.192	0.177	0.102	0.136
900	0.196	0.179	0.106	0.137
910	0.198	0.175	0.112	0.166
920	0.189	0.178	0.115	0.136
930	0.194	0.179	0.102	0.128
940	0.191	0.174	0.106	0.134
950	0.196	0.180	0.102	0.131
960	0.196	0.180	0.102	0.122
970	0.182	0.176	0.111	0.130
980	0.199	0.198	0.109	0.145
990	0.189	0.171	0.102	0.136
1000	0.220	0.175	0.113	0.134
1010	0.199	0.176	0.118	0.133
1020	0.191	0.175	0.117	0.141
1030	0.206	0.178	0.122	0.139
1040	0.195	0.163	0.106	0.135
1050	0.197	0.163	0.111	0.140
1060	0.201	0.172	0.101	0.138
1070	0.195	0.160	0.104	0.146
1080	0.207	0.172	0.108	0.134
1090	0.199	0.184	0.103	0.132

1100	0.199	0.190	0.116	0.138
1110	0.209	0.173	0.113	0.141
1120	0.198	0.187	0.107	0.133
1130	0.201	0.182	0.109	0.131
1140	0.209	0.160	0.112	0.137
1150	0.196	0.188	0.117	0.138
1160	0.209	0.176	0.111	0.131
1170	0.201	0.172	0.109	0.130
1180	0.200	0.178	0.105	0.135
1190	0.204	0.160	0.107	0.131
1200	0.198	0.172	0.112	0.136
1210	0.229	0.167	0.118	0.136
1220	0.192	0.172	0.120	0.139
1230	0.197	0.178	0.112	0.130
1240	0.201	0.176	0.116	0.119
1250	0.196	0.170	0.106	0.126
1260	0.204	0.160	0.103	0.140
1270	0.201	0.171	0.105	0.140
1280	0.200	0.177	0.110	0.127
1290	0.204	0.177	0.105	0.145
1300	0.197	0.165	0.107	0.141
1310	0.202	0.184	0.103	0.137
1320	0.202	0.181	0.100	0.133
1330	0.200	0.182	0.108	0.135
1340	0.203	0.176	0.106	0.143
1350	0.197	0.173	0.108	0.143
1360	0.196	0.174	0.112	0.139
1370	0.199	0.172	0.107	0.135
1380	0.200	0.171	0.107	0.130
1390	0.202	0.182	0.111	0.137
1400	0.202	0.175	0.108	0.133
1410	0.198	0.175	0.107	0.151
1420	0.209	0.175	0.112	0.130
1430	0.189	0.174	0.109	0.122
1440	0.204	0.170	0.112	0.138
1450	0.201	0.177	0.110	0.136
1460	0.200	0.153	0.116	0.117
1470	0.204	0.188	0.110	0.134
1480	0.197	0.179	0.103	0.130
1490	0.202	0.175	0.113	0.128

1500	0.202	0.179	0.108	0.136
1510	0.200	0.176	0.124	0.129
1520	0.203	0.177	0.106	0.134
1530	0.197	0.171	0.111	0.140
1540	0.196	0.186	0.109	0.143
1550	0.199	0.171	0.098	0.136
1560	0.200	0.183	0.110	0.139
1570	0.202	0.168	0.109	0.124
1580	0.202	0.175	0.115	0.140
1590	0.198	0.167	0.109	0.129
1600	0.209	0.188	0.111	0.125
1610	0.189	0.171	0.112	0.137
1620	0.197	0.173	0.102	0.140
1630	0.201	0.170	0.105	0.133
1640	0.195	0.172	0.115	0.148
1650	0.207	0.178	0.113	0.131
1660	0.199	0.169	0.109	0.128
1670	0.199	0.173	0.110	0.139
1680	0.209	0.182	0.102	0.138
1690	0.198	0.160	0.104	0.141
1700	0.201	0.166	0.107	0.129
1710	0.209	0.175	0.113	0.127
1720	0.196	0.177	0.121	0.127
1730	0.209	0.157	0.117	0.150
1740	0.201	0.182	0.118	0.125
1750	0.200	0.177	0.117	0.134
1760	0.204	0.171	0.109	0.136
1770	0.189	0.164	0.115	0.132
1780	0.193	0.185	0.120	0.138
1790	0.189	0.180	0.109	0.139
1800	0.191	0.181	0.100	0.133
1810	0.197	0.172	0.120	0.129
1820	0.189	0.176	0.111	0.140
1830	0.193	0.169	0.114	0.124
1840	0.192	0.180	0.112	0.126
1850	0.188	0.181	0.103	0.131
1860	0.196	0.183	0.117	0.134
1870	0.210	0.181	0.115	0.135
1880	0.193	0.181	0.105	0.129
1890	0.195	0.178	0.114	0.155

1900	0.192	0.179	0.119	0.120
1910	0.196	0.171	0.111	0.132
1920	0.198	0.173	0.108	0.133
1930	0.189	0.177	0.113	0.134
1940	0.194	0.171	0.117	0.157
1950	0.191	0.176	0.117	0.136
1960	0.196	0.175	0.121	0.140
1970	0.196	0.179	0.109	0.126
1980	0.182	0.180	0.117	0.138
1990	0.170	0.169	0.117	0.126
2000	0.172	0.179	0.118	0.135
2010	0.173	0.184	0.112	0.125
2020	0.171	0.189	0.116	0.140
2030	0.170	0.179	0.115	0.128
2040	0.176	0.176	0.114	0.135
2050	0.179	0.176	0.115	0.141
2060	0.182	0.175	0.109	0.145
2070	0.178	0.179	0.112	0.135
2080	0.180	0.182	0.113	0.143
2090	0.175	0.170	0.115	0.142
2100	0.179	0.174	0.105	0.144
2110	0.181	0.173	0.114	0.140
2120	0.180	0.176	0.117	0.149
2130	0.183	0.187	0.106	0.132
2140	0.181	0.176	0.110	0.144
2150	0.185	0.173	0.113	0.133
2160	0.196	0.177	0.111	0.150
2170	0.196	0.179	0.117	0.134
2180	0.182	0.167	0.115	0.143
2190	0.170	0.174	0.111	0.139
2200	0.172	0.167	0.115	0.126
2210	0.173	0.180	0.117	0.136
2220	0.171	0.174	0.115	0.142
2230	0.170	0.174	0.123	0.137
2240	0.176	0.175	0.108	0.136
2250	0.179	0.182	0.112	0.150
2260	0.182	0.179	0.111	0.147
2270	0.178	0.172	0.117	0.141
2280	0.180	0.179	0.114	0.140
2290	0.175	0.186	0.113	0.148

1900	0.192	0.179	0.119	0.120
1910	0.196	0.171	0.111	0.132
1920	0.198	0.173	0.108	0.133
1930	0.189	0.177	0.113	0.134
1940	0.194	0.171	0.117	0.157
1950	0.191	0.176	0.117	0.136
1960	0.196	0.175	0.121	0.140
1970	0.196	0.179	0.109	0.126
1980	0.182	0.180	0.117	0.138
1990	0.170	0.169	0.117	0.126
2000	0.172	0.179	0.118	0.135
2010	0.173	0.184	0.112	0.125
2020	0.171	0.189	0.116	0.140
2030	0.170	0.179	0.115	0.128
2040	0.176	0.176	0.114	0.135
2050	0.179	0.176	0.115	0.141
2060	0.182	0.175	0.109	0.145
2070	0.178	0.179	0.112	0.135
2080	0.180	0.182	0.113	0.143
2090	0.175	0.170	0.115	0.142
2100	0.179	0.174	0.105	0.144
2110	0.181	0.173	0.114	0.140
2120	0.180	0.176	0.117	0.149
2130	0.183	0.187	0.106	0.132
2140	0.181	0.176	0.110	0.144
2150	0.185	0.173	0.113	0.133
2160	0.196	0.177	0.111	0.150
2170	0.196	0.179	0.117	0.134
2180	0.182	0.167	0.115	0.143
2190	0.170	0.174	0.111	0.139
2200	0.172	0.167	0.115	0.126
2210	0.173	0.180	0.117	0.136
2220	0.171	0.174	0.115	0.142
2230	0.170	0.174	0.123	0.137
2240	0.176	0.175	0.108	0.136
2250	0.179	0.182	0.112	0.150
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2280	0.180	0.179	0.114	0.140
2290	0.175	0.186	0.113	0.148

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1910	0.196	0.171	0.111	0.132
1920	0.198	0.173	0.108	0.133
1930	0.189	0.177	0.113	0.134
1940	0.194	0.171	0.117	0.157
1950	0.191	0.176	0.117	0.136
1960	0.196	0.175	0.121	0.140
1970	0.196	0.179	0.109	0.126
1980	0.182	0.180	0.117	0.138
1990	0.170	0.169	0.117	0.126
2000	0.172	0.179	0.118	0.135
2010	0.173	0.184	0.112	0.125
2020	0.171	0.189	0.116	0.140
2030	0.170	0.179	0.115	0.128
2040	0.176	0.176	0.114	0.135
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2070	0.178	0.179	0.112	0.135
2080	0.180	0.182	0.113	0.143
2090	0.175	0.170	0.115	0.142
2100	0.179	0.174	0.105	0.144
2110	0.181	0.173	0.114	0.140
2120	0.180	0.176	0.117	0.149
2130	0.183	0.187	0.106	0.132
2140	0.181	0.176	0.110	0.144
2150	0.185	0.173	0.113	0.133
2160	0.196	0.177	0.111	0.150
2170	0.196	0.179	0.117	0.134
2180	0.182	0.167	0.115	0.143
2190	0.170	0.174	0.111	0.139
2200	0.172	0.167	0.115	0.126
2210	0.173	0.180	0.117	0.136
2220	0.171	0.174	0.115	0.142
2230	0.170	0.174	0.123	0.137
2240	0.176	0.175	0.108	0.136
2250	0.179	0.182	0.112	0.150
2260	0.182	0.179	0.111	0.147
2270	0.178	0.172	0.117	0.141
2280	0.180	0.179	0.114	0.140
2290	0.175	0.186	0.113	0.148

3100	0.178	0.178	0.084	0.134
3110	0.180	0.164	0.078	0.130
3120	0.175	0.176	0.083	0.133
3130	0.179	0.166	0.078	0.127
3140	0.181	0.162	0.075	0.138
3150	0.185	0.177	0.074	0.143
3160	0.196	0.174	0.078	0.132
3170	0.178	0.163	0.076	0.128
3180	0.180	0.172	0.079	0.138
3190	0.175	0.185	0.076	0.131
3200	0.170	0.161	0.071	0.145
3210	0.176	0.168	0.072	0.130
3220	0.181	0.171	0.076	0.132
3230	0.181	0.171	0.076	0.132
3240	0.185	0.170	0.079	0.135
3250	0.196	0.161	0.084	0.135
3260	0.178	0.162	0.078	0.130
3270	0.180	0.162	0.083	0.134
3280	0.175	0.177	0.078	0.134
3290	0.170	0.179	0.075	0.129
3300	0.176	0.173	0.074	0.130
3310	0.181	0.172	0.078	0.137
3320	0.180	0.168	0.070	0.136
3330	0.183	0.170	0.078	0.128
3340	0.181	0.165	0.075	0.139
3350	0.181	0.160	0.071	0.136
3360	0.185	0.171	0.080	0.134
3370	0.170	0.163	0.071	0.131
3380	0.176	0.166	0.074	0.131
3390	0.181	0.176	0.078	0.138
3400	0.181	0.160	0.076	0.132
3410	0.185	0.164	0.079	0.141
3420	0.196	0.177	0.076	0.137
3430	0.178	0.177	0.071	0.135
3440	0.180	0.159	0.077	0.132
3450	0.175	0.172	0.070	0.136
3460	0.170	0.160	0.073	0.131
3470	0.176	0.156	0.076	0.143
3480	0.181	0.150	0.075	0.131
3490	0.180	0.154	0.071	0.138

3500	0.183	0.180	0.080	0.124
3510	0.181	0.175	0.071	0.134
3520	0.181	0.173	0.079	0.134
3530	0.185	0.170	0.076	0.135
3540	0.178	0.174	0.083	0.144
3550	0.180	0.175	0.078	0.130
3560	0.175	0.173	0.075	0.139
3570	0.179	0.161	0.074	0.135
3580	0.181	0.170	0.078	0.139
3590	0.180	0.171	0.076	0.138
3600	0.183	0.172	0.079	0.130
3610	0.181	0.169	0.076	0.126
3620	0.185	0.173	0.071	0.133
3630	0.196	0.179	0.077	0.133
3640	0.178	0.178	0.070	0.138
3650	0.180	0.174	0.073	0.129
3660	0.175	0.175	0.076	0.140
3670	0.179	0.178	0.079	0.131
3680	0.153	0.179	0.076	0.134
3690	0.143	0.179	0.071	0.135
3700	0.194	0.166	0.077	0.123
3710	0.181	0.176	0.070	0.137
3720	0.178	0.180	0.073	0.139
3730	0.171	0.181	0.076	0.134
3740	0.171	0.174	0.075	0.131
3750	0.175	0.179	0.071	0.131
3760	0.173	0.171	0.080	0.132
3770	0.173	0.188	0.071	0.137
3780	0.171	0.177	0.079	0.126
3790	0.171	0.186	0.076	0.132
3800	0.174	0.187	0.083	0.127
3810	0.156	0.185	0.080	0.123
3820	0.171	0.176	0.071	0.120
3830	0.172	0.179	0.079	0.126
3840	0.169	0.186	0.076	0.128
3850	0.167	0.192	0.083	0.141
3860	0.167	0.171	0.078	0.136
3870	0.175	0.186	0.075	0.137
3880	0.179	0.184	0.084	0.137
3890	0.153	0.176	0.078	0.106

3900	0.143	0.176	0.083	0.135
3910	0.194	0.178	0.078	0.129
3920	0.181	0.175	0.075	0.134
3930	0.178	0.175	0.074	0.133
3940	0.171	0.171	0.078	0.130
3950	0.178	0.174	0.070	0.135
3960	0.180	0.178	0.078	0.126
3970	0.175	0.174	0.075	0.141
3980	0.179	0.172	0.071	0.134
3990	0.181	0.177	0.076	0.134
4000	0.180	0.176	0.071	0.149
4010	0.183	0.176	0.077	0.132
4020	0.181	0.180	0.070	0.133
4030	0.185	0.186	0.073	0.123
4040	0.196	0.175	0.076	0.150
4050	0.178	0.156	0.075	0.138
4060	0.180	0.166	0.071	0.126
4070	0.175	0.155	0.080	0.135
4080	0.179	0.179	0.071	0.149
4090	0.153	0.176	0.079	0.126
4100	0.143	0.171	0.076	0.126
4110	0.194	0.174	0.083	0.128
4120	0.181	0.175	0.078	0.130
4130	0.178	0.159	0.075	0.134
4140	0.171	0.179	0.074	0.130
4150	0.171	0.178	0.078	0.130
4160	0.175	0.177	0.076	0.130
4170	0.173	0.176	0.079	0.133
4180	0.194	0.172	0.076	0.136
4190	0.181	0.178	0.071	0.131
4200	0.178	0.171	0.077	0.125
4210	0.171	0.173	0.070	0.131
4220	0.171	0.175	0.073	0.128
4230	0.181	0.177	0.076	0.122
4240	0.178	0.177	0.079	0.123
4250	0.171	0.172	0.079	0.128
4260	0.171	0.173	0.076	0.134
4270	0.175	0.176	0.071	0.139
4280	0.173	0.175	0.077	0.135

Appendix B: Corrosion Rate Default Matrix for CUI

Table N-3—Corrosion Rate Default Matrix—Carbon Steel External Corrosion

Operating Temperature, °F	Driver		
	Marine / Cooling Tower Drift Area (mpy)	Temperate (mpy)	Arid / Dry (mpy)
10 or less	0	0	0
11 to 60	5	3	1
61 to 120	2	1	0
121 to 200	5	2	1
201 to 250	1	0	0
> 250	0	0	0