CHAPTER 1
INTRODUCTION

1.1 Background of Study

Carbon steel pipeline is widely used in oil and gas industry due primarily to the lower cost of the material compared to corrosion resistant alloys. The selection of carbon steel pipeline in oil and gas project is feasible and technically justifiable with the implementation of corrosion inhibitor. Previously corrosion inhibitor efficiency is taken into account as one of the most important criteria during the selection of the corrosion inhibitor to be used in the field, but since the year of 2000, several studies had carried out and found that corrosion inhibitor availability is as important as corrosion inhibitor efficiency.

According to the trend of NACE paper publications [7, 9, and 10], corrosion availability concept started to be accepted in the year of 2001 with the publication of Carbon Steel Pipeline Corrosion Engineering: Life Cycle Approach by Ian Rippon. Where criteria contributed to corrosion inhibitor availability were identified and was taken into account for life cycle cost analysis. [9] In 2002, Bill Hedges, Dominia Paisley and Richard Woolham published their paper "Corrosion Inhibitor Model", where corrosion inhibitor availability concept was introduced. They showed how important of corrosion inhibitor availability concept effect on the corrosion rate of the pipeline. The trend of the corrosion inhibitor availability concept can be summarized as in Figure 1.1.

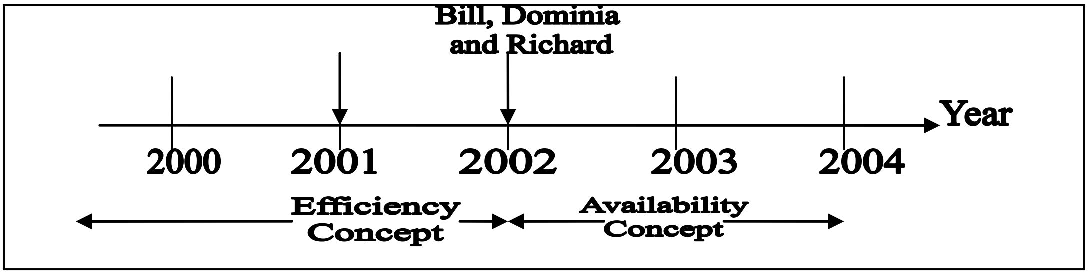


Figure 1.1: Trend of corrosion inhibitor implementation from efficiency to availability concept

1.2 Problem Statement

In the stage of material selection, carbon steel piping is the most preferable material to be used in the field to transport the crude oil or gas to the shore because carbon steel piping is more economical compare to other corrosion resistance alloy. Carbon steel piping is allowed to be use in the field when the prediction corrosion rate of the piping is below 6mm/year and with the condition corrosion inhibitor application is needed on the carbon steel piping in order to control the corrosion rate in the pipeline.

In the design of the corrosion inhibitor system, corrosion availability normally used is 95%, but the reality during operation, it is impossible to achieve availability of corrosion inhibitor as high as 95% except the corrosion inhibitor system design with a high reliability costs. Thus during the operational of the pipeline low corrosion inhibitor availability reported, there were 2 possible scenarios occurred with the low corrosion inhibitor availability. First scenario is that although there is low availability of the corrosion inhibitor in the system but the corrosion rate of the piping is still in the range of targeted corrosion rate. But in another hand, the low corrosion inhibitor availability in the system will cause the corrosion rate of the pipelines increases.

For the first scenario where the corrosion rate of the pipeline is still within the range of uninhibited corrosion rate although low corrosion inhibitor availability, this show that the corrosion inhibitor availability applied during the design stage was over design. The first scenario piping system does not require the high corrosion inhibitor availability system. The over design of the corrosion inhibition system in order to achieve the high corrosion inhibitor availability consume a lot of cost, thus the unnecessary cost in design occurred and causing capital expenditure for that particular project will be high.

On the other hand, for the second scenario where corrosion rate of the pipeline increase due to the low corrosion inhibitor availability and may lead to failure of the piping system due to corrosion. Failure in the piping system will consume more cost in term of lost in production, impact to environment due to the leakage of the crude oil or gas to the environment and cost to repair the failure piping. The overall process of the problem statement that occurred on carbon steel piping is described in Figure 1.2.

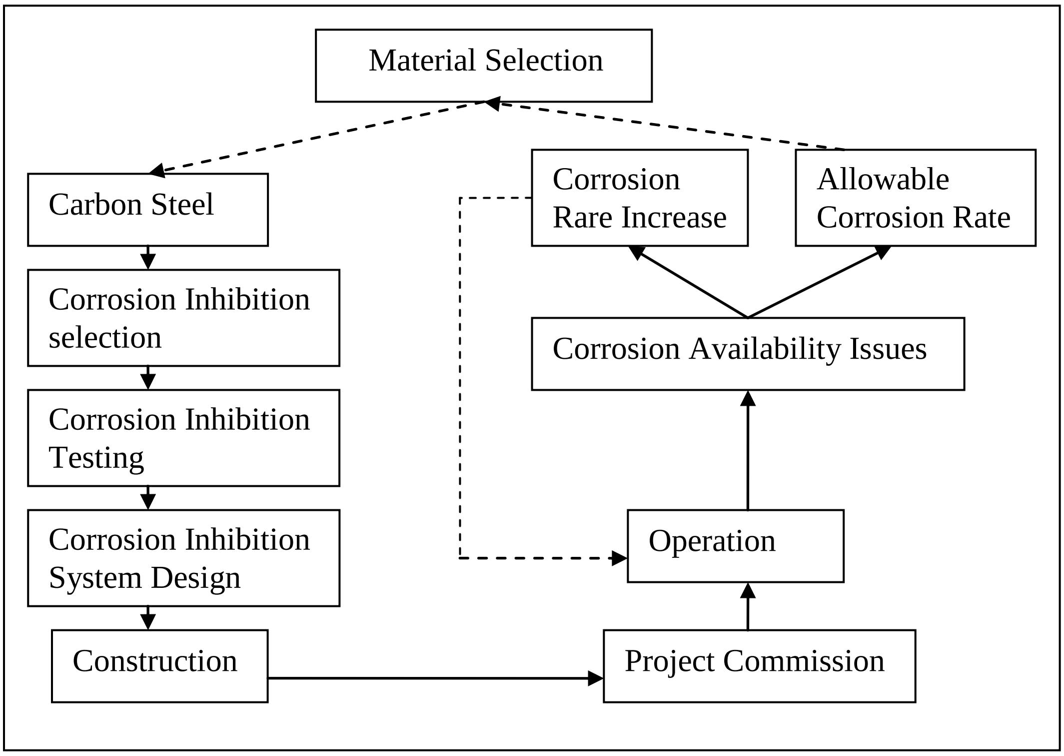


Figure 1.2: Flow chart describing problem statement of material selection involving corrosion inhibitor availability issues

Low corrosion inhibitor availability maybe due to several factors such as chemical pumps failure, inhibitors stocks unavailability, others facilities failure and operators human errors. Studies should be carried out in more detail in order to identify the factors that cause the low availability of the corrosion inhibitor in the system.

1.3 Objective and Scope of Studies

The purpose of this project study is to study corrosion inhibitor availability effect on piping integrity and corrosion rate. This project study had being divided into 2 sections, the first section is base on the field data and the second section is based on the laboratory experiments. Field data was obtained from PETRONAS Carigali Sdn. Bhd. (PCSB). Field study determines how corrosion inhibitor availability effect on the piping integrity. Data on corrosion rate of the piping system will be collected from the fields and comparison will be carried out and find out whether the CI availability in the field affect the corrosion rate.

The second section of this project is based on the laboratory testing. Corrosion inhibitor availability will be study base on the corrosion inhibitor dosage. The optimum dosage of corrosion inhibitor represents high availability of corrosion inhibitor in the system, and dosage below the optimum dosage is low corrosion inhibitor availability. These experiments will be divided again into 3 sections, where the first section will determine the optimum dosage of the corrosion inhibitor, second section is to study the effect of low corrosion availability effect on the corrosion rate, and the third section will be verification of the optimum dosage corrosion inhibitor.

Objective of this project is to show corrosion inhibitor availability effect on the piping integrity and corrosion rate. Study base on the field data will show corrosion inhibitor availability effect on the piping integrity. While for the laboratory testing will study on the corrosion inhibitor availability effect on the corrosion rate.

In this study, corrosion inhibitor dosage is taken as the indication of corrosion inhibitor availability. Thus, laboratory experiments will be divided into 3 section and each sections have their own objective. The first section of the laboratory will determine the optimum corrosion inhibitor dosage needed for the brine prepare in the laboratory. The second section of the laboratory will study on the effect of corrosion inhibitor availability on the corrosion rate. The third section of the laboratory experiment is to justify the efficiency of the corrosion inhibitor under the optimum dosage.

CHAPTER 2
LITERATURE REVIEW

2.1 CO_2 Corrosion in Oil and Gas Industry

The impact of corrosion on the oil and gas industry will impact the capital expenditure, operational expenditure, health, safety and environment. Majority of the corrosion failure occurred on the pipelines is related to CO_2 corrosion. According to M.B. Kernani, the cost of corrosion is 30 cents (USD) for the production of each barrel of oil production. CO_2 corrosion had caused increases in cost and safety issues. Table 2.1 showed the percentage of CO_2 corrosion account for the incident. [11]

Table 2.1: Percentage of incidents CO_2 corrosion contribute [11]

Events	Percentage (%)
Safety Incidents	25
Turnover	2.8
Tangible Asset	2.5
CAPEX increase	8.5
Lost Production	5
Lifting Cost Increase	11.5

Carbon steels and low alloy steels in the aqueous CO_2 environment could be susceptible to general corrosion and localized attack. When carbon dioxide dissolves in the presence of a water phase, carbonic acid forms, which is corrosive to carbon steel. Numerous studies have been carried out to investigate the corrosion mechanisms of carbon steel immersed in de-ionized water and brine solutions saturated with carbon dioxide. Most of them are based on experiments in stirred beakers and small diameter flow loops.

The overall corrosion process could be divided into four steps. The first step is the dissolution of carbon dioxide in the aqueous solution to form the various reactive species, which takes part in the corrosion reaction. The second step is the transportation of these reactants to the metal surface. The third step involves the electrochemical reactions (anodic and cathodic) taking place at the metal surface. [5] The fourth step is the transportation of the corrosion products to the bulk of the solution. These can be shown as:

1) Formation of reactive species in the bulk

$CO_2 + H_2O \rightarrow H_2CO_3$

$H_2CO_3 \rightarrow HCO_3^- + H^+$

$HCO_3^- \rightarrow CO_3^{2-} + H^+$

2) Transportation of reactants (bulk to surface)

H_2CO_3 (bulk) $\rightarrow H_2CO_3$ (surface)

HCO_3^- (bulk) $\rightarrow HCO_3^-$ (surface)

H^+ (bulk) $\rightarrow H^+$ (surface)

3) Electrochemical reactions at the surface

$2H_2CO_3 + 2e^- \rightarrow H_2 + 2HCO_3^-$

$2HCO_3^- + 2e^- \rightarrow H_2 + 2CO_3^{2-}$

$2H^+ + 2e^- \rightarrow H_2$

$Fe \rightarrow Fe^{2+} + 2e^-$

4) Transportation of products (surface to bulk)

Fe^{2+} (surface) $\rightarrow Fe^{2+}$ (bulk)

CO_3^{2-} (surface) $\rightarrow CO_3^{2-}$ (bulk)

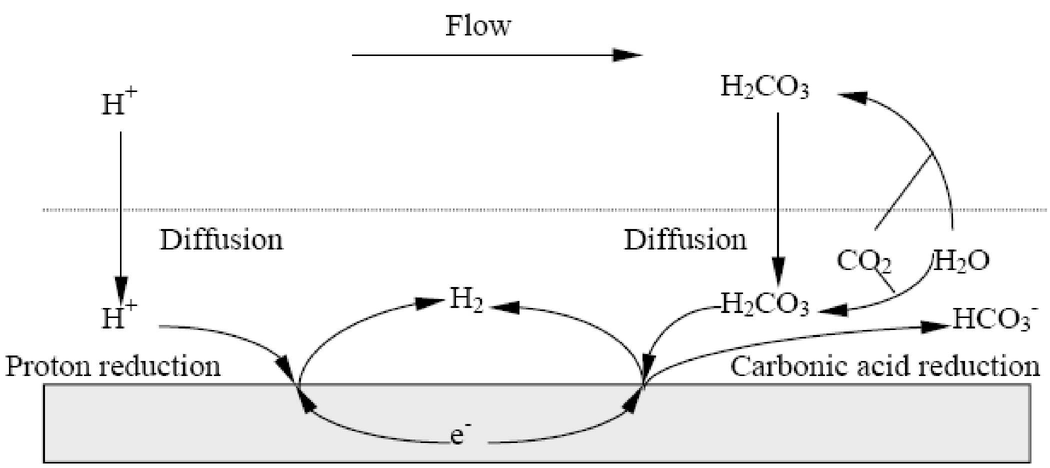


Figure 2.1: Simple model for CO_2 corrosion model

According to S. Nesic, a simplified model for carbon steel corrosion under multiphase flow conditions, as shown in Figure 2.1. [14] The protons have to diffuse from the bulk region through the boundary layer to the metal surface, while the transport flux of carbonic acid needs to reflect both diffusion of H_2CO_3 and hydration of CO_2 in the boundary layer. He also suggested that the diffusion of hydrogen ions and carbonic acid is the rate-determining step.

2.2 Material Selection Process

Design stage in PETRONAS is according to PETRONAS Technical Standards, Design and Engineering Practice, Selection of Materials for Life Cycle Performance where they will go through 3 stages of evaluation before making decision on the material selection as shown in Figure2.2. [12]

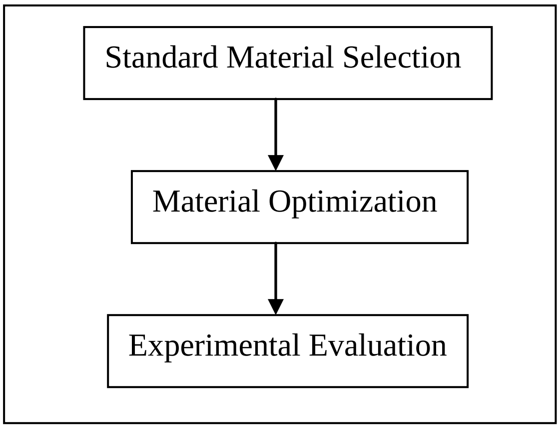


Figure 2.2: Flow chart of material Selection process during design stage.

Material selection processes can be divided into 2, main process stream item and secondary process stream. For the main process stream item the initial material selection carried out at concept selection phase. While secondary process stream items material selection taken place at Front End Engineering design phase (FEED) in order to optimize, more refined judgment on corrosion rate, life production and risk assessment to ensure the material selected or proposed is fit for purpose.

For long lead or bulk item (pipelines and down hole tubing) key material decision made at concept selection stage. For new project where involve tie in existing installation, the materials in place and their current condition should be ascertained in the concept selection phase. In this phase, operational personal need to be involves.

Selection process is structured as 3-tier system based on: (1) Standard Material Selection, (2) Material optimization, and (3) Experimental evaluation.

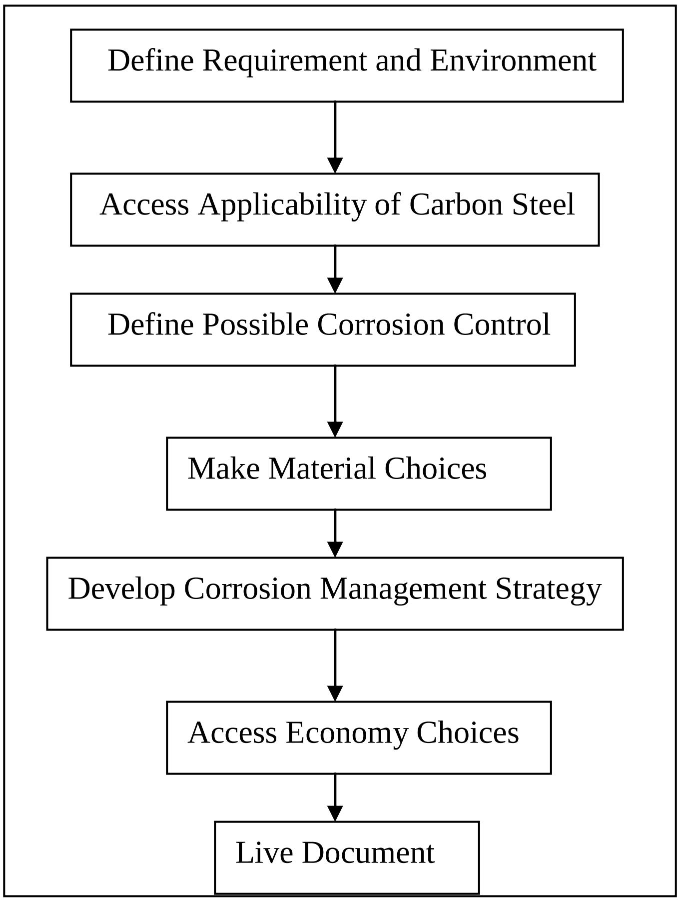


Figure 2.3: Flow Chart of process of Standard Material Selection

This literature review gave explanation on the standard material selection system. Standard material selection includes the following steps: (1) define requirement and environment, (2) Assess the applicability of carbon steel and define possible corrosion control options, (3) make material choices, (4) develop corrosion management strategy, (5) assess economic choices 1, and (6) live documents.

First step is to require information and review of factors affecting materials. The internal and external environment must be defined. For internal environment included the definition of corrosion threat and flow condition evaluation. External environmental for pipelines are defining the pipelines buried or above ground, corrosive environment, external surface temperature, onshore or offshore and others.

In this first step, we also need to take into account on the low temperature service during startup period, exceptional conditions and non-operational conditions.

Assess the applicability of carbon steel and define possible corrosion control options. We need to define the service life corrosion of the carbon steel by estimating the wall thickness reduction during the service life. Then we should consider CO2 corrosion that carbon steel facing. Corrosion and cracking in sour service also need to be taken into account. Then finally look into the corrosion mitigation for carbon steel component. Table of classification of service life corrosion, wall thickness loss that allow to use carbon steel is shown in Table 2.1 below.

Table 2.2: Reference Table for material selection decision making base on predicted corrosion rate

Environmental conditions				**Materials selection for piping**	**Piping class**[6]
SLC (mm)	**Temp** (°C)	**pH_2S** (mbar)	**NaCl** (g/L)		
< 1	< 200	< 3.5	Any	CS with 1 mm c.a.	1410, 1450, or 1470
< 3	< 200	< 3.5	Any	CS with 3 mm c.a.	1430 or 1490
3-6	< 80	< 3.5	Any	CS with 3 mm c.a[5]. If only limited life is required see [7]	1430 or 1490
< 1	< 200	< 100	Any	SSCC and HIC-resistant steel with 1 mm c.a.	1420 or 1460
< 3	< 200	< 100	Any	SSCC and HIC-resistant steel with 3 mm c.a.	1440
3-6	< 80	< 100	Any	SSCC and HIC-resistant steel with 3 mm c.a[5]. If only limited life is required see [8]	1440
≥ 6	<120	< 8	100	AISI 316L	3430
≥ 6	< 200	< 10	< 250	22Cr Duplex	3832
≥ 6	< 60	< 15	100	AISI 316L	3430
≥ 6	< 200	< 20	< 250	25Cr Duplex	
≥ 6	< 200	< 80	< 50	25Cr Duplex	

Table 2.2 (continue): Reference Table for material selection decision making base on predicted corrosion rate

Environmental conditions				Materials selection for piping	Piping class[6]
SLC (mm)	**Temp** (°C)	**pH_2S** (mbar)	**NaCl** (g/L)		
≥ 6	< 200	< 350	< 1 (1000 ppm)	22Cr Duplex	3832
≥ 6	< 120	< 900	< 10	AISI 316L	3430
≥ 6	< 200	< 1,000	< 1 (1000 ppm)	25Cr Duplex	
≥ 6	< 200	< 10,000	< 200	6Mo	
≥ 6	< 200	< 14,000	< 250[9]	Alloy 825	
≥ 6	< 200	< 36,000	< 250[9]	Alloy 28[10]	
≥ 6	< 240	< 30,000	< 250[9]	Alloy 625[11]	
≥ 6	<100[4]	Any	Any	GRP	

When doing material selection choices, service life corrosion figure can be used for the materials selection, if the corrosion rate is known from the service experience or prediction. Otherwise, basic operating condition data can be used to obtain the possible materials options.

Develop corrosion management strategy. Corrosion management is where feed forward of the design intent and implied constraints with respect to operations, maintenance and inspection to the operation phase, inspection or monitoring data collection, inspection or monitoring data analysis and reporting or feedback of experience with respect to possible operations maintenance and inspection improvements and updates to design standards. In corrosion management, we also have corrosion circuit where we group together parts of individual process stream that have similar corrosion environments and shall defined it in material selection stage.

Documentation that describe the strategy of material selection and corrosion control should include: (1) corrosion management manual, where including material selection, corrosion control strategy, key performance indicators for corrosion control system, (2) populated corrosion management database, (3) maintenance reference plan, and (4) risk based assessment (can be included in CMM).

Corrosion mitigation methods that can be used are sphering and pigging, inhibition requirement and gas drying. In this project we will focus on the inhibition requirement. The documentations that needed in the inhibition are details of inhibition process, chemicals to be used, concentration and required availability of inhibition system. Responsibility of the operation staffs are highlighted in CMM, including the facility operation procedures and detailed reviewed of uninhibited events. Key performances indicators compiled and reviewed data rolled up annually and determine annualized assessment of corrosion inhibitor availability.

On the economic aspects of material selection is base on the life cycle costing, guidance from ISO 15663-1 and shall be perform for material selection in main stream. Factors to be included in the LCC are: (1) corrosivity evaluation, (2) erosion evaluation taking into account solids particles, high velocity liquid, including high frequency slugging and droplets, (3) consequences of material selection for required wall thickness and thereby equipments weight, (4) possibility of satisfactory corrosion inhibition, (5) fabrication/ welding and installation costs related to pipe wall thickness, (6) for pipelines, the effect of wall thickness or pipe weight upon installation methods and cost, (7) extra costs related to carbon steel, and (8) access and cost for replacement of system of compartment. The equation of LCC is shown below.

$$LCC = \sum_{n=1}^{N} \frac{AC + IC + OC + LP + (RC - SC)}{(1+i)^n}$$

LCC	-	Total life cycle cost;
AC	-	Initial acquisition cost of materials, phased by expenditure year;
IC	-	Initial installation (fabrication) costs, phased by expenditure year;
OC	-	Operating plus maintenance costs;
LP	-	Lost (deferred) production costs during downtime;
RC	-	Replacement materials costs;
SC	-	Residual value of replaced materials;
Σ	-	Sum from year one to N, the desired life of the application;
i	-	Real interest rate (from projected long-term interest rate and inflation rate);
n	-	Year of the event;
N	-	Design life.

2.3 Corrosion Inhibitor Selection

BP corrosion inhibitor selection study is as follows: solubility/ disperisibility screening, bubble test screening, rotating screening (if there are still a large number of candidates) and flow loop screening. [2]

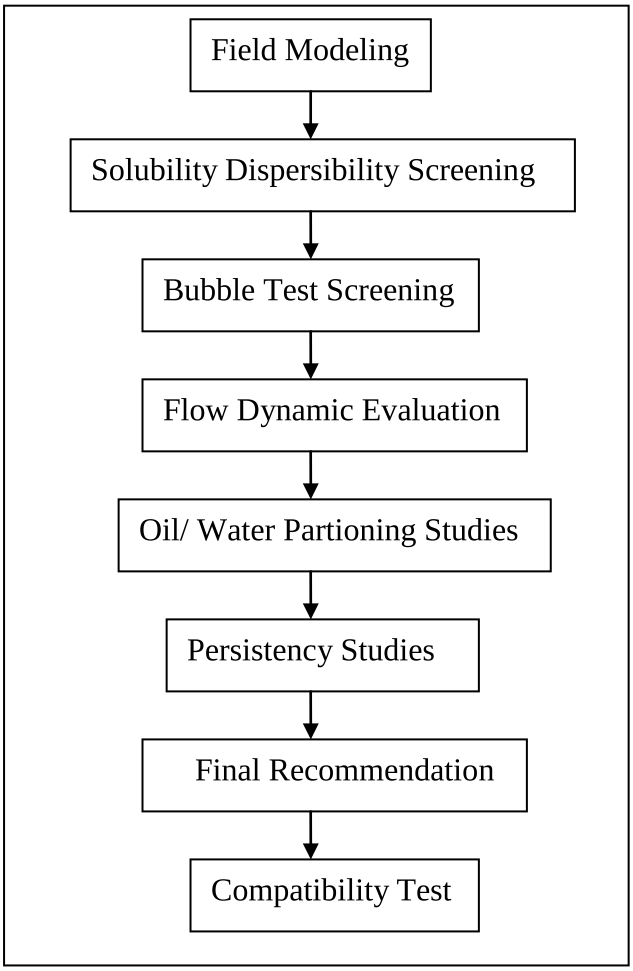


Figure 2.4: Flow Chart of corrosion inhibitor selection process.

The study would start with large candidates of corrosion inhibitors (around 20) which will gradually reduced at each stage. The rotating cylinder screening will be only used if dynamic tests are required on large number of candidates. The solution also includes any other oil field chemical such as scale inhibitors and demulsifier.

The most important is to start the selection is fully characterize the system, such as flow regimes, range of wall shear stresses experienced in the pipeline and identify critical areas where inhibition may be difficult due to local disturbance of flow. Full water analysis and operational condition required so that water chemistry used in the tests can be accurately simulated. Uninhibited fields' samples of crude oil should always be used whenever possible.

Then, come to the solubility screening. All products in BP selection first qualitatively checked for their solubility in brine and oil. Corrosion inhibitors must be soluble in both brine and maltenes in order to proceed to the next stage of testing. In bubble test screening, a large number of corrosion inhibitors packages are to be screened, this allow a rapid screening to be undertaken and immediate identification of any inhibitors which are incompatible with the test solution. Effect of the inhibitor concentration on performance also studied at this stage along with the time to reach maximum inhibition. Typical oil field corrosion inhibition takes up to 40 minutes to reach maximum inhibition. Products with adsorption time more than this is rejected. Adsorption kinetic also used to rank the inhibitors in a short-list for the next stage of testing.

The preferred candidates evaluated by the rotating cylinder electrode and the flow loop test. This is flow dynamic evaluation stage. Rotating cylinder electrode is useful intermediate step which can reduce the number of candidates going forward to the final flow loop stage. Further test provides quantitative assessment of susceptibility to film break down for each candidate inhibitor.

For oil/ water partitioning studies is to obtain an accurate estimate of injection rate and to ensure full protection in areas of water drop out or wetting. The assessment is best base on corrosion performance rather than analytical approach. Two test can be done in order to do partition studies, they are equilibrium partitioning and partitioning kinetics test. Persistency studies is carried out in order to determine the effectiveness of the inhibitor during operation upsets, extreme changes in flow rate, or interruption in chemical deployment.

Final recommendation is made with the availability of the performance data, partitioning data and also economic considerations. Environmental friendliness is another factor that needs to be taken into consideration. The selected corrosion inhibitor will go through compatibility test with other oil field chemicals. Flow loop test used in the compatibility test to determine the effect on inhibitor adsorption kinetic and corrosion rate. If the corrosion inhibitor is compatible then it can go forward for field trailing.

2.4 Corrosion Inhibitor Availability Model

According to Bill Hedges, Dominia Paisley and Richard Woolham in their paper title The Corrosion Availability Model, Corrosion 2000, Paper 34. [9]

Benefits of corrosion Inhibitor Availability model are:

- Focus on the required corrosion rate
- Removes focus from the mean corrosion rate
- Accounts for realistic achievable corrosion rate
- Identifies the importance of the availability of corrosion inhibitors
- Accounts for interruption or the absence of inhibitor from time to time
- Does not allow dangerous low corrosion allowance to be used

Distribution of corrosion rate is not a single corrosion rate but range of values distributed about a mean in the log normal form. The role of corrosion inhibitor is to reduce the spread of corrosion rate. And eliminate extremely high values of corrosion rate. The mean and most frequent corrosion rate may have the significantly lower than the target value. Dosage rate is based on the water phase.

Corrosion inhibitor availability model used formula shown below to calculate the corrosion availability of the system according to the life time period of that particular system or equipment, in this case is the piping lifetime.

A% = 100 x Time Inhibitor is actually added at or above the minimum dosage /lifetime

Corrosion allowance of the piping is determined during the design stage used the formula below to formulate the corrosion allowance for the piping. The corrosion allowance calculated based on the prediction of the corrosion rate of the piping during the availability of the corrosion inhibitor and without the corrosion inhibitor. The formulas below show how corrosion allowance related to the corrosion inhibitor availability.

Corrosion Allowance = Inhibited CA + Uninhibited CA

Corrosion Allowance = (CR_i x A%/100 x life time) + (Cr_u x A%/100 x life time)

Normally inhibited corrosion rate is 0.1mm/year. Thus, the corrosion allowance formula can be simplified to:

Corrosion Allowance = (0.1x A%/100 x life time) + (CRu x [1-A%/100] x life time)

According to corrosion inhibitor availability model the risk categories for certain project is as shown in Table A1 shown in the appendix.

From Prudoe Bay data, corrosion inhibitor dosage is recorded down yearly and plotted in the graph. The data showed that corrosion inhibitor dosage do affect the integrity of the pipeline. Figure 2.5 shows dosage of corrosion inhibitor injected into the piping system from year 1990 to 1999. Figure 2.6 shows the corrosion rate of the piping system from the year 1990 to 1999 with different corrosion inhibitor dosage.

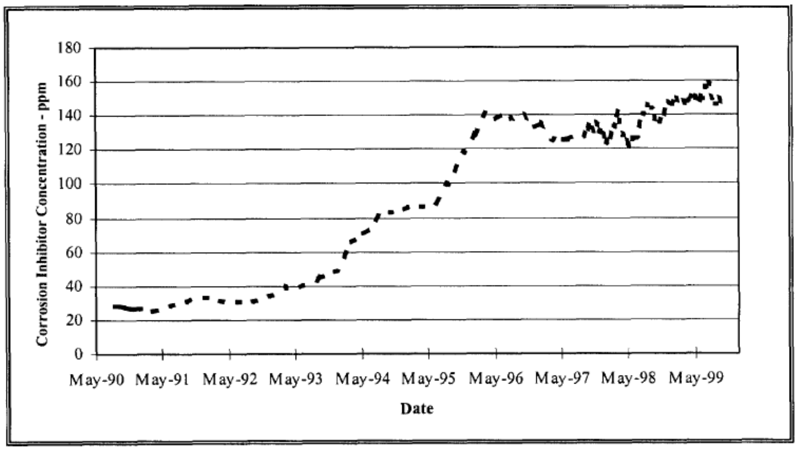


Figure 2.5: Prudhoe Bay Corrosion Inhibitor Dosage

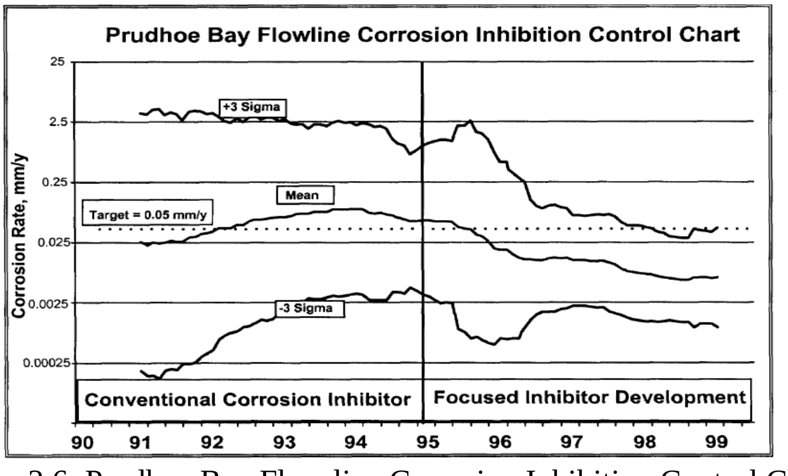


Figure 2.6: Prudhoe Bay Flow line Corrosion Inhibition Control Chart

The study used the method of corrosion inhibitor dosage to prove corrosion inhibitor availability effect integrity of the pipeline. They started with the dosage of 25 ppm of corrosion inhibitor and increase the dosage yearly and study the corrosion rate trend. The corrosion rate trend decrease as the corrosion inhibitor dosage increase. The higher the dosage of the corrosion inhibitor meaning availability of the corrosion inhibitor is high. By the year of 1995, it found the optimum dosage of the corrosion inhibitor where corrosion rate of the piping is the minimum and decreasing. From their study result it is shown that corrosion inhibitor availability does affect the corrosion rate of the piping because at low concentration corrosion inhibitor (= low availability) will have higher corrosion rate and optimum concentration (=high availability) will have lower corrosion rate.

Besides that the justification for corrosion inhibitor availability base on the corrosion inhibitor dosage can be strengthen by using the data and facts given by J.W. Palmer, in his published paper, title corrosion control by firm forming control, he stated that the low corrosion availability, in his case he also used corrosion inhibitor dosage as his main issue for corrosion inhibitor availability, the low corrosion availability will effect the performance of the corrosion inhibitor, insufficient of corrosion inhibitor dosage equivalent to low availability of corrosion inhibitor.[10] Low availability of corrosion inhibitor will not decrease the corrosion rate to the optimum inhibited corrosion rate, low corrosion inhibitor availability will reduce the life cycle of the pipeline.

The data from his study is shown in Figure 2.7 and 2.8.

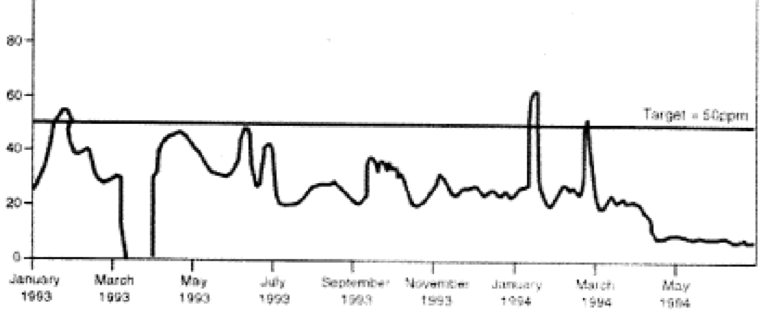


Figure 2.7: Poor corrosion inhibitor dosage shown will affect the service life of the flow line.

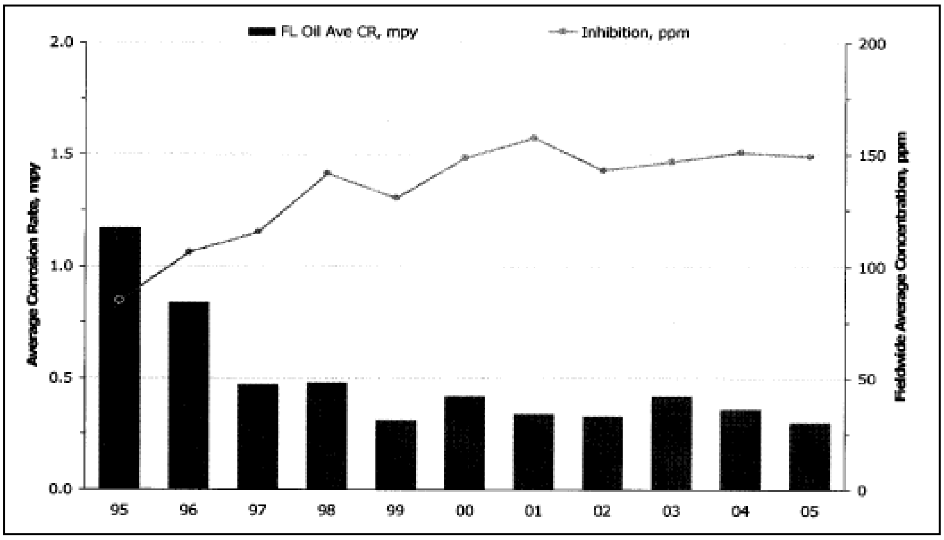


Figure 2.8: Integration between the corrosion rate of the flow line and the concentration (dosage) of the corrosion inhibitor in the slug flow.

2.5 Criteria Contribute To CI availability

Corrosion inhibitor availability is contributed by many factors. Base on the literature review that had being made from NACE International published papers [7, 10, and 12] the criteria that contribute to the CI availability had being identified. The criteria that determine CI availability are:

1. Suitability of the inhibitor in the application.
2. Inhibitor Injection Pumps.
3. Inhibitor tanks.
4. Report on inhibitors used to responsible corrosion engineer.
5. Corrosion monitoring system response
6. Comprehensive review of uninhibited events.
7. Persistency.
8. Allowable period of time for uninhibited events
9. Training for operators
10. Corrosion engineering involvement.
11. Key performance indicators set for operations technicians and corrosion engineers.
12. Corrosion inhibitor dosage

Several criteria that contribute to the corrosion inhibitor availability are briefly described in this subtopic.

2.5.1 Suitability of the inhibitor in application

All inhibitors must be tested in the lab and prove the effectiveness and suitability of the CI in the system that going to apply. If inhibitor does not suitable in the application system, availability of the CI, availability = 0. All CI must be suitable in their application system in order to evaluate for the CI availability of the system.

2.5.2 Inhibitor Injection Pump

2.5.2.1 Frequent and time take for corrective maintenance per year

From the record of the pumps used in the CI system, identify the frequent and time taken for the corrective maintenance. From there, we can estimate the CI availability of the field if there is no backup pump available in the system.

2.5.2.2 Backup Pumps

Availability of one backup pump may increase the CI availability system to 100% depend on the reliability of the pumps. The reliability of the pumps can be identified with the criteria in the section 4.2.1. More back pumps greater the CI availability.

2.5.3 Inhibitor tanks

Monitoring inhibitor tanks level. Manual check on the tanks level by operator on the daily basis gave a lower availability compare to the automated alarm. Volume of the tank is depend on the injection rate that required by the system, and the space available in the platform. The volume of the tanks will determine the frequent of the top up of the inhibitors in the tank and ensure the availability of the inhibitors in the storage tanks. Some platform uses intermediate bulk storage as their tanks. Schematic drawing of the inhibitor tank is shown in the appendix section Figure 8.

2.5.4 Training for operators

This is another important criterion to have a high CI availability system. Training such as monitoring the performance of the pumps, more on reliability of the pumps, vibration monitoring, preventive maintenance in order to ensure there is no sudden failure of the equipments. Refreshment training is to ensure operators aware about their task in maintaining the CI availability system.

2.5.5 Comprehensive and Review of Uninhibited Events

The record of the uninhibited events can contribute to the corrosion inhibitor availability. Complete record on the review of uninhibited events and prevention actions had been carried out will contribute to the increase of the corrosion inhibitor availability. This is because there is history data on the failure or uninhibited events, the same failure or uninhibited events will not reoccurred if actions had been taken.

2.5.6 Key performance indicators

Key performance indicator set for the operators will reduce the possibility of faulty from the operators during the operation of the corrosion inhibition system. For example the corrosion inhibitor dosage to be injected into the pipelines, with key performance indicator prepared injection of corrosion inhibitor will be very consistence according to the optimum dosage that the pipelines desired. Thus increase the corrosion inhibitor availability in the system.

2.5.7 Corrosion monitoring response

Corrosion monitoring response will reduce the time of period to identify the uninhibited events in the system. With more efficient corrosion monitoring response, uninhibited events can be identify in the early stage and cut short the uninhibited duration time by doing corrective actions on the faulty that had being identified. Thus corrosion inhibitor availability will increase.

2.5.8 Corrosion Inhibitor Dosage

Corrosion inhibitor dosage is one the main factor that being discussed in the most of the papers published by NACES. The corrosion inhibitor dosage is the resultant from several criteria that affect the corrosion inhibitor availability. Corrosion inhibitor dosage also can be representing the corrosion inhibitor availability in general. Thus, corrosion inhibitor dosage is taken as the main factor that contributes to the corrosion inhibitor availability.

Dosage of corrosion inhibitor depends on the volume of the service fluids. The higher the volume of the service fluid, the higher the dosage is required. Low dosage of corrosion inhibitor in the pipelines representing low corrosion inhibitor availability, this low corrosion inhibitor availability will lead to increase in the corrosion rate.

High corrosion inhibitor availability represented optimum dosage of corrosion inhibitor in the pipelines, resulting corrosion inhibitor giving the optimum corrosion inhibitor efficiency. Over dosage of corrosion inhibitor will not improve the corrosion inhibitor efficiency where the reduction in corrosion rate wills not less than the optimum inhibited corrosion rate.

2.6 Standard Test Method for Conducting Potentiodynamic Polarization Resistance Measurement

Polarization resistance measurement is used to determine the corrosion rate of metal in a specific environment. ASTM 59 described the experimental procedure for polarization resistance measurements which can be used for calibration of equipment and verification of experimental technique.

The test method can be utilized to verify the performance of polarization resistance measurement equipments. Polarization resistance can be related to the rate of general corrosion for metals at or near their corrosion potential, it is an accurate and rapid way to measure the general corrosion rate. This method also can be used as a way to rank inhibitor in the order of resistance to general corrosion.

The test procedures standard included are:

1. Test solution should be prepared, and the standard test cell requires 900ml of test solution where the temperature must be maintained at 30 degree Celsius within 1 Celsius.
2. Test cell must purge at 150 cm^3 /min with an oxygen free gas. The purge is started at least 30 min before specimen immersion and continue through out the test.
3. Working electrode is prepared, and experiment must be conducted within 1 hour of the preparing electrode. Preparation including sequential wet polishing with 240 grit and 600 grit SiC paper. Surface area of the specimen is determined to the nearest of 0.01 cm^2 and subtract the area under the gasket.

4. Prior to immersion of the specimen, it is degreased with a solvent such as acetone and rinsed with distilled water. The time delay between rinsing and immersion should be minimal.
5. The test specimen is transferred into the test cell and position the Luggin probe tip to 2 to 3 mm from the test electrode surface. The diameter of the tip must be not more than 1 mm.

2.7 Protocol to Test Corrosion Inhibitor in Laboratory

According to A.J McMahon, written in his papers, “Round Robin” Validation of Test Methods and Bubble Test Protocol. There are several set standard operating procedures to establish confidence in the repeatability and reproducibility of corrosion inhibitor test methods. (1995)

In BP Round Robin protocol consists of uninhibited and inhibited test under the simulated condition. Equivalent of the hydrodynamic conditions are used in each type of apparatus. He also stated that in order to produce solution, the quantities of salt cannot be added straight in to the 1 liter of distilled water, because this will produce volume of water greater than 1 liter. To prevent scaling and precipitation, chloride is dissolve first and follow by dissolution of the carbon dioxide and finally bicarbonate.

Standard steel is important because high sulfur content of carbon steel thus S element will act as corrosion inhibitor and affects the corrosion rate. The active surface preparation as stated in this protocol. Cleanliness of the equipment also important to obtain reliable data, the recommended cleaning after inhibitor are deionsed water rinse, toluene rinse, petroleum ether rinse, acetone rinse and deionised water rinse at least 5 times.

Corrosion measurement in the testing of corrosion inhibitor can use weight loss measurements and linear polarization resistance (LPR) to monitor the corrosion rates. In LPR the working electrode in three electrode system is wept from 0 to -10 mV at 30MV/min. The polarization resistance is converted into a corrosion rate using Stern-Geary constant of 27.3 mV.

Shear stress in the bubble test is less than 1.3 Pa and it is well below other facilities included in the Round Robin exercise (7 Pa). From BP test facilities under a set of standard condition, the baseline corrosion rate for bubble test were in the region 120 mpy, it is lower than the flow loop data but are still within 30% of De Waard and Milliams predicted values of 134 mpy. [2]

"Bubble test" is a simple test which can be set up reasonably quickly and is ideal for rapidly carrying out a large number of tests. This test also conducted in the first stage of corrosion inhibitor selection, or for screening a wide range of field of field conditions. [2] The main limitation of the bubble test is shear stresses in the stirred solution are significantly lower than experienced in the pipeline. For a 3.8cm magnetic stirrer rotated with 300ppm outside of the edge will only produce 1.2 Pa, the value at the electrode slightly less than this. The operating procedure for bubble test is very crucial during the cleaning of the cell or called vessel as discussed previously in the Round Robin validation test method by McMahon.

CHAPTER 3
METHODOLOGY

Corrosion inhibitor availability study will be based on the analysis of real field data designed as Pipeline A, B and laboratory simulation.

3.1 Pipeline Database

The pipeline database is summarized in Table 3.1.

Table 3.1: General Information of Pipeline A and Pipeline B

	Pipeline A	Pipeline B
Service Fluid	Sales Gas	Crude Oil
Size	24"	10"
Year of Construction	1979	1982
Operating Temperature	32.2 ^{o}C	55 ^{o}C
Operating Pressure	1378 psi (94.9442 bar)	377 psi (25.9753 bar)
Corrosion Inhibitor	Yes	Yes

The database is compiled from PMO Pipeline Database, Pipeline Annual Integrity Review provided by Casa Impian, Internal Pipeline Inspection Database and Integrity Surveillance Data Summary.

The flow of the methodology in analyzing the pipeline database is showed in Figure 3.1.

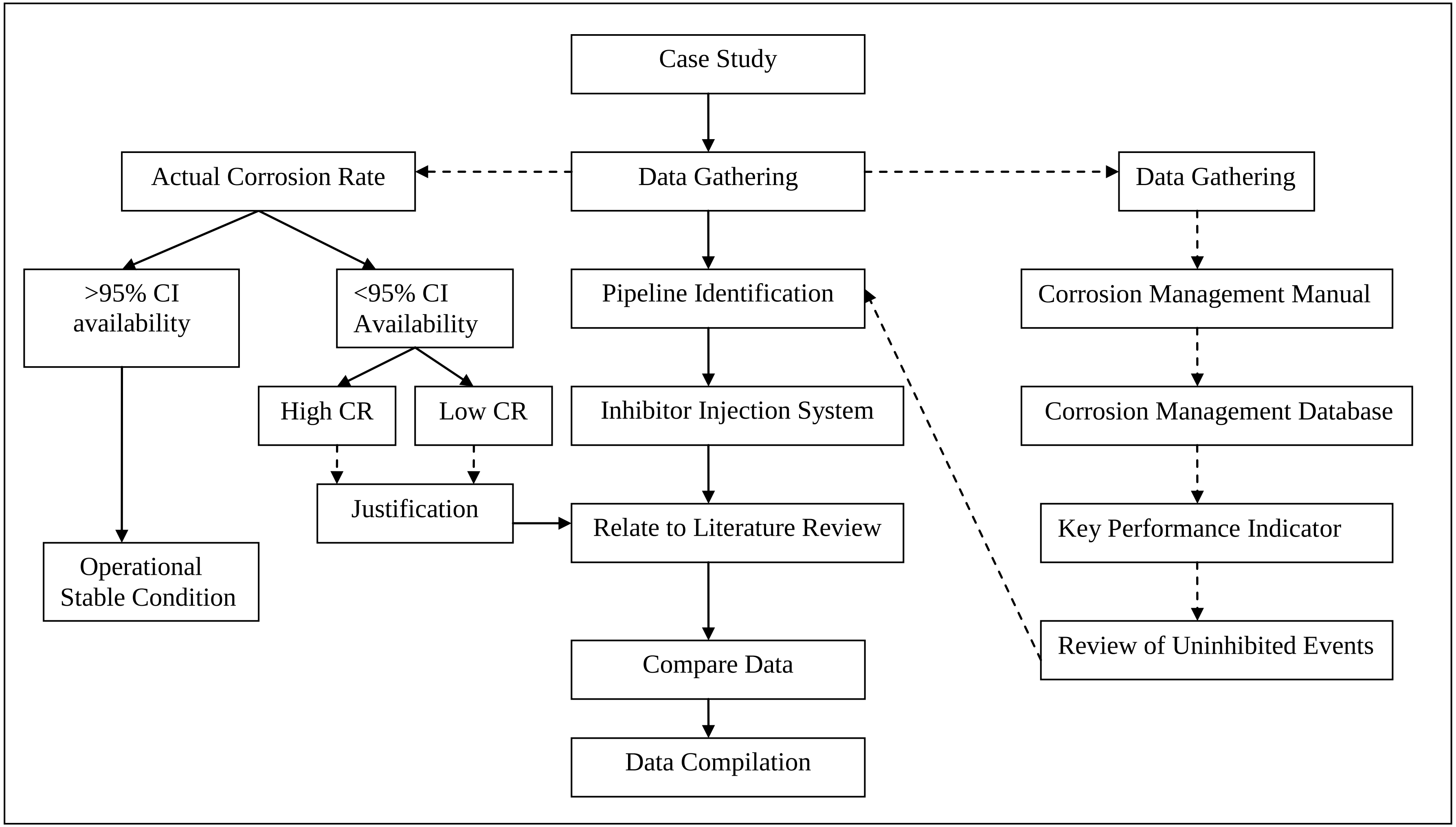


Figure 3.1: Flow chart of the summary of the methodology base on field case study.

3.2 Laboratory Simulation Test

Laboratory simulation test is conducted to determine the effect of corrosion inhibitor availability to the corrosion rate of carbon steel.

In this laboratory test corrosion inhibitor dosage will be taken as the main cause that affects the corrosion inhibitor availability. Different dosage of the corrosion inhibitor will be injected into the testing environment solution and the corrosion rate of each test will be recorded down to determine the effect of the corrosion inhibitor dosage (availability) on the corrosion rate. Methodology of the experiment is as describe in the flow chart shown in the Figure 3.2.

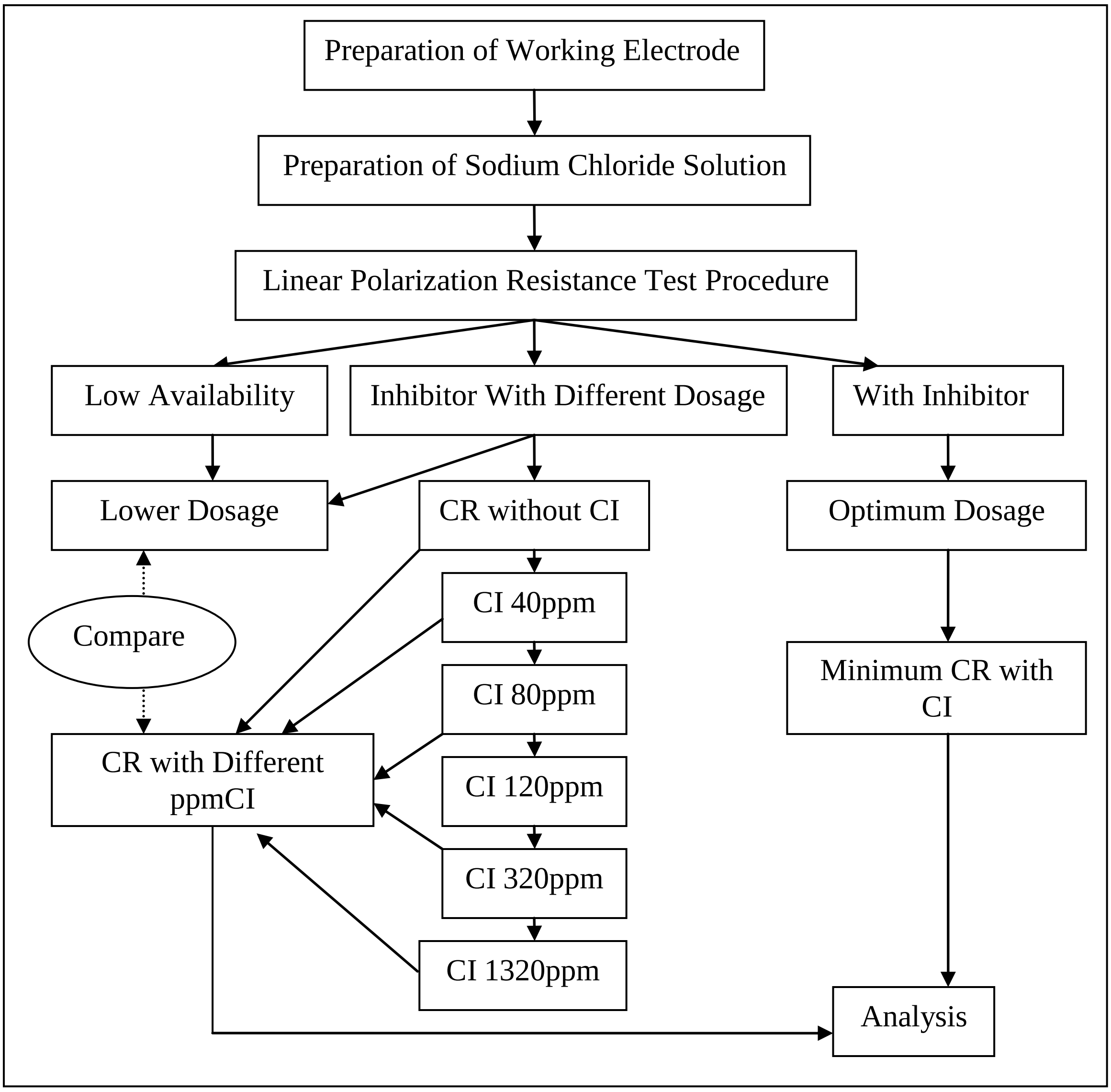


Figure 3.2: Flow chart of the methodology involve in laboratory testing

3.2.1 Laboratory Set-up

The set-up for the laboratory test using electrochemical measurement method of linear polarization resistance experiments is showed in Figure 3.3 and Figure 3.4. The test assembly consists of one-liter glass cell bubbled with CO_2 gas. The required test temperature is set through a hot plate. The electrochemical measurements are based on a three-electrode system, using a commercially available potentiostat with a computer control system. The reference electrode used is a saturated calomel electrode (SCE) and the auxiliary electrode is a platinum electrode.

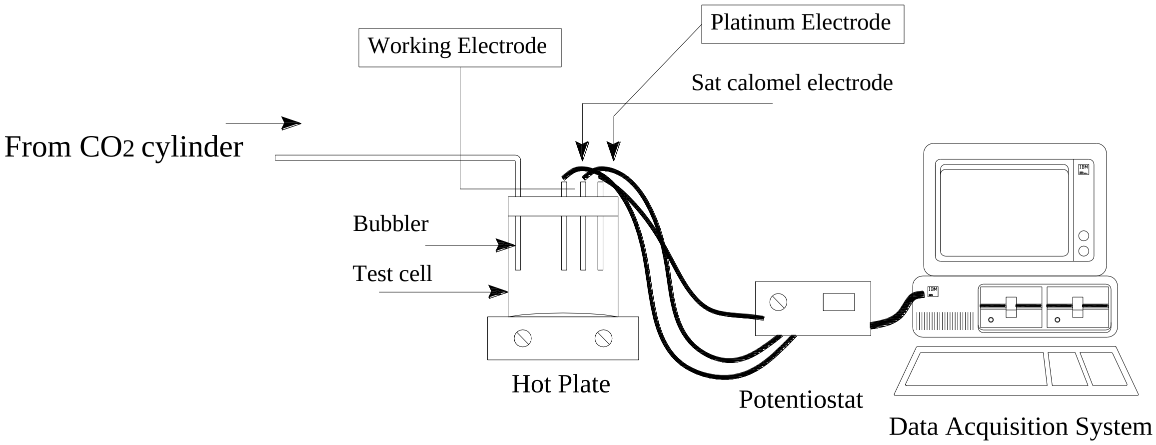


Figure 3.3: Schematic diagram for static experimental set-up

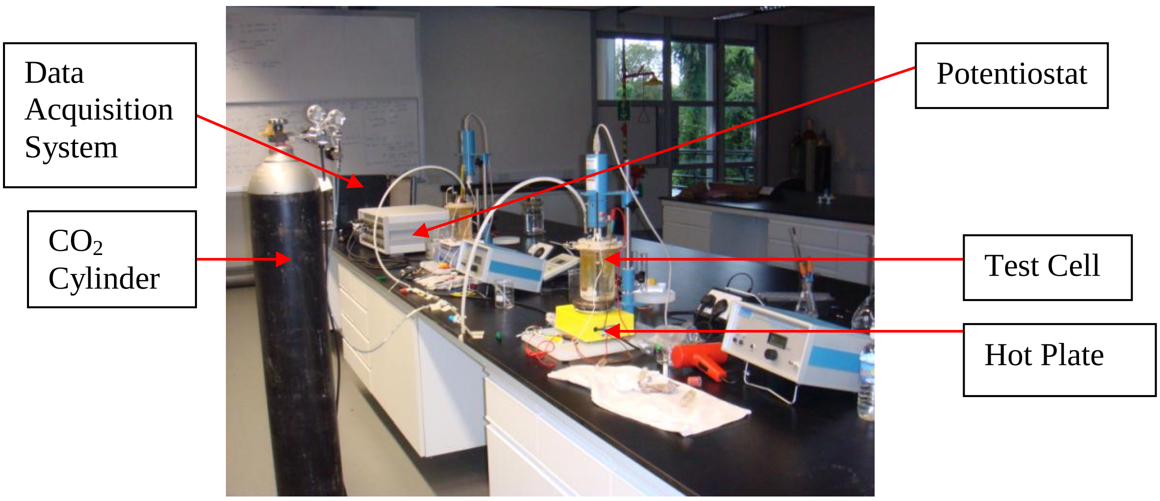


Figure 3.4: Real experiment set up in the laboratory

Corrosion rate is measured by linear polarization resistance method carried out is based on the ASTM G59-97, Standard Method for conducting potentiodynamic polarization resistance measurement. [5] Detail test procedure is given in Section 2.6.

3.2.2 Material

The working electrode or sample in this experiment is mild steel (EN 24). The composition of the mild steel EN 24 as shown below: [6]

Table 3.2: Composition of Plain Carbon Steels

Samples	Plain Carbon Steels	
Composition	Min (%)	Max (%)
Carbon	0.35	0.45
Silicon	0.05	0.35
Manganese	0.60	1.00
Sulphur		0.06
Phosphorus		0.06

The preparations of the working electrode are as follow:

1. The samples were spot welded with copper wire.
2. After that, it was mounted with epoxy by cold mounting and then polished to 800-grade finish using silicon carbide paper.
3. Finally, it was degreased and rinsed with deionizer water and ethanol. The working electrode is shown in Figure 3.5.

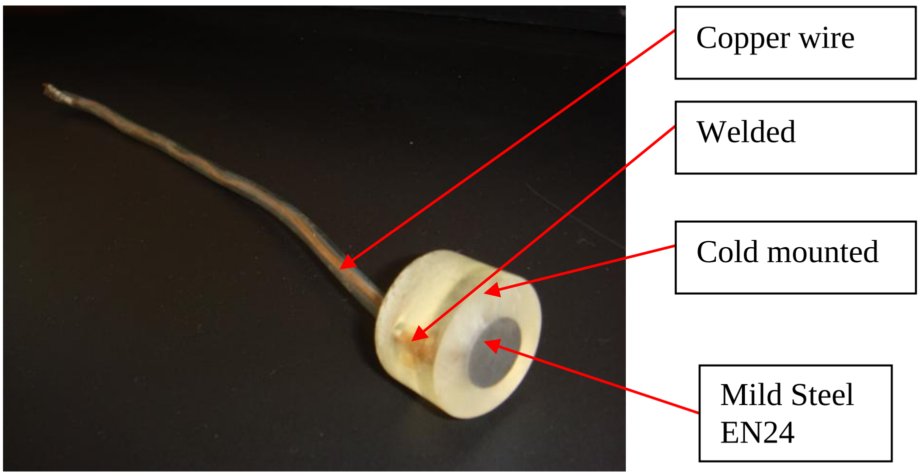


Figure 3.5: Photo of EN24 working electrode.

3.2.3 Preparation of Solutions

The solutions were prepared from the 3% NaCl solution is saturated with CO_2 by purging for at least one hour prior to the exposure of electrode. The pH of the solution could be adjusted by adding an amount of 1M $NaHCO_3$. The pH value is checked by microcomputer pH-meter METTLER-TOLEDO Model 320, which had been calibrated using standard buffer solutions.

3.2.4 Experiment Environment

The environment for the laboratory had being set to temperature 40^oC, acidity of the solution is pH5 and 1 bar of carbon dioxide purge in the solution through out the experiment to provide the environment of CO_2 corrosion.

3.2.5 Addition of Corrosion Inhibitor

Corrosion Inhibitor used in this experiment is MACES 22-04, as shown in Figure 3.6, manufactured by MACES Sdn. Bhd. The composition of the corrosion inhibitor is mainly amine with proportion of 30-60% according to the safety datasheet provided by the manufactured company. The safety data sheet of the corrosion inhibitor is attached in the appendix section.

Corrosion inhibitor dosage injected into the cell for the experiment is according to reference from a few papers published by NACE International. According to Bill Hedges, Dominia Paisley and Richard Woolham the corrosion inhibitor injected into the flow line of service fluid with 60% water cut is around 140ppm. Micropipette is used to measure the accurate volume of the corrosion inhibitor into the solution.

The volume of corrosion inhibitor added into the solution is base on parts per million (ppm) according to the volume of solution used in the experiment. For this experiment, the volume of the 3% NaCl used is 1 liter. Thus 1ppm of corrosion inhibitor in this experiment is equivalent to 1µL. This experiment starts with adding corrosion inhibitor of 40 µL into the solution to make the solution 40ppm of corrosion inhibitor in the solution.

Figure 3.6: Corrosion Inhibitor provided by MACES.

3.2.6 Experiment Procedures

The laboratory to study corrosion inhibitor availability had being divided into 3 sections. The procedures of the experiments for the 3 sections are nearly the same and the difference is during the addition of the corrosion inhibitor dosage.

Experiments procedures are as per described below:

1. Solution medium of sodium chloride 3% prepared, 30g of sodium chloride is mixed into the distilled water of 1 liter.
2. Working electrode prepared as per describe in the section 3.2.2. And Setting up of the equipment for the laboratory test as per described in section 3.2.1.
3. Purging of the carbon dioxide gas started and continuous purging for half an hour until the carbon dioxide is saturated in the solution. The indication of the cell is saturated with carbon dioxide can be tested with the pH meter when it indicate the reading of pH nearly 3.8.
4. Heat up the solution to 40^{o}C to provide the desired temperature for the experiment, and sodium bicarbonate is added into the solution to increase the pH of the solution to 5. Once the environment of the experiment achieve.
5. For the first section of the experiment, corrosion inhibitor is not added into the solution, thus proceed to the step 8 once the working electrode is placed in the cell. After one hour of test run, 40µL corrosion inhibitor added into the solution and run for another hour, followed by another 40µL to make the solution 80ppm of corrosion inhibitor. After another hour of 80ppm corrosion inhibitor test run, 200µL of corrosion inhibitor is added in to produce

320ppm corrosion inhibitor solution. Finally 1mL of corrosion inhibitor added in the solution to produce 1320ppm of corrosion inhibitor solution.

6. Second section of the experiment is to determine the effect of low corrosion inhibitor availability effect on the corrosion rate. Thus, lower dosage of corrosion inhibitor is added into the solution and study the corrosion rate due to the low corrosion inhibitor availability. In this case, corrosion inhibitor of dosage 20ppm, 30ppm, 50ppm, 60ppm and 70 ppm is used to study the trend of the low corrosion inhibitor availability affect on the corrosion rate.
7. The third section of this experiment is to do confirmation testing on the optimum dosage of corrosion inhibitor without adding it batch by batch. 80ppm of corrosion inhibitor is added into the solution and tested for one hour.
8. Once the chemicals and electrodes added into the solution, access the data acquisition system, in this laboratory is computer connected to the ACM Instruments Version 5, run Gill 12 Weld Tester Serial No. 1350 –Sequencer and the Core Running software.
9. Key in all the parameters that set for the measurement of the experiment into the Sequencer software.
10. Run the ACM Instruments and data is gathered automatically into the ACM Analysis Version 4, where they record down the Linear Polarization Resistances and calculate the corrosion rate using the formula that will be discuss in the Section 3.2.7.

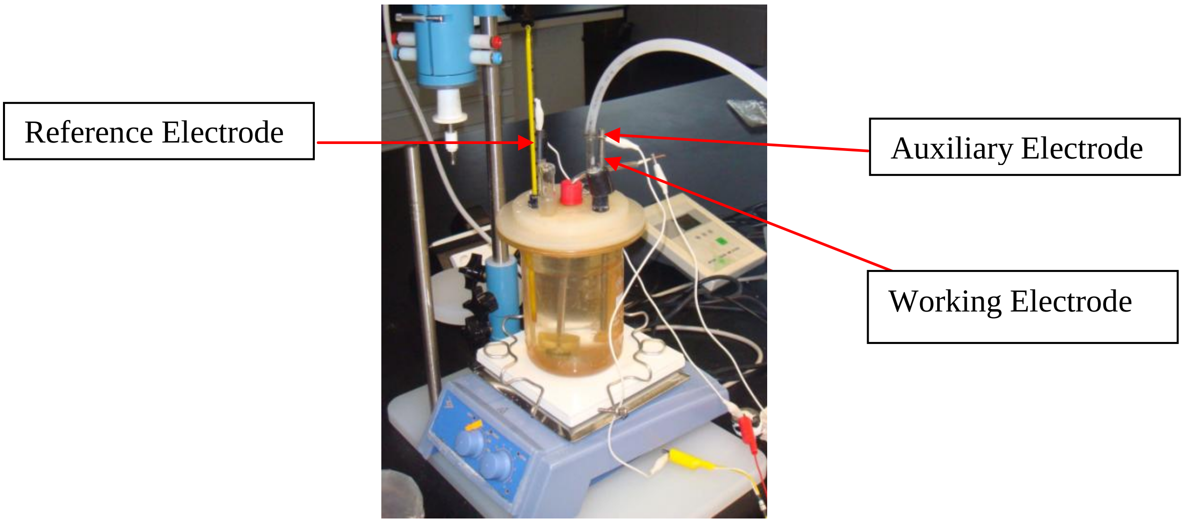


Figure 3.7: Static bubble test using Linear Polarization Resistance method set up in the laboratory.

3.2.7 Theory behind calculation

From the linear polarization resistance test, we can determine the corrosion rate of the sample. The theory of the calculation for linear polarization is as shown below: [5]

The corrosion current density is related to polarization resistance by Stern_Geary coefficient, B. The Stern-Geary Constant, B, is approximated as 25 mV for all pH.

$$i_{corr} = B/R_p$$

The dimension of R_p is ohm-cm2, i_{corr} is mA/cm^2, and B is in V. B also can be written as:

$$B = \frac{b_a\ b_c}{2.303(b_a + b_c)}$$

Where ba, bc is the Tafel slope for cathodic and anodic reaction. According to the soft ware that we are using in the lab to do the calculation, Tafel Slope, B used in the calculation is 26.

The corrosion rate, CR in mm/year can be determined from the formula shown below:

$$CR = 3.27 \times i_{corr}\ EW/\ \text{density of the corroding material}$$

Where, EW is the equivalent weight of the corroding species in grams and the density of the corroding material is in g/cm^3. In this case equivalent weight of iron is 27.92 g and density of the corroding material is iron, thus, iron density is 7.8 g/cm^3

CHAPTER 4
RESULT AND DISCUSSION

The corrosion inhibitor availability analysis of both field data and laboratory simulation are described in the following section.

4.1 Corrosion Inhibitor Availability Analysis: Field Pipeline Data

Corrosion prediction of both pipelines with corrosion inhibitor is 0.11 mm/year and 0.25 mm/year respectively. However based on the inspection intelligent pigging data from year 1986 to 2003 showed that Pipeline B reported severe corrosion rate compare to Pipeline A where no detectable internal defect found in the pipeline. The summary of inspection intelligent pigging data is showed in Table 4.1.

Table 4.1: Summary for intelligent pigging data for Pipeline A and B

Pipeline No.	Size and Service	Installation Year	Length (km)	Year of Inspection	Number of location Metal Lost Detected
Pipeline A	24" Gas	1982	48.7	1986	0
				1994	0
Pipeline B	10" Crude	1979	4.4	1989	5
				1994	3
				1997	2
				2003	34

The metal loss reported was in the range of 30 to 50% wall thickness. During the year of 1989, parts of Pipeline B had been replaced. Taking the worst case the corrosion rate of the Pipeline B is 0.63mm/year from 1979 to 1989 and 0.45mm/year from 1989 to 2003. The actual performance of corrosion inhibitor as compared to the predicted inhibited corrosion rate is shown in Figure 4.1 and Figure 4.2.

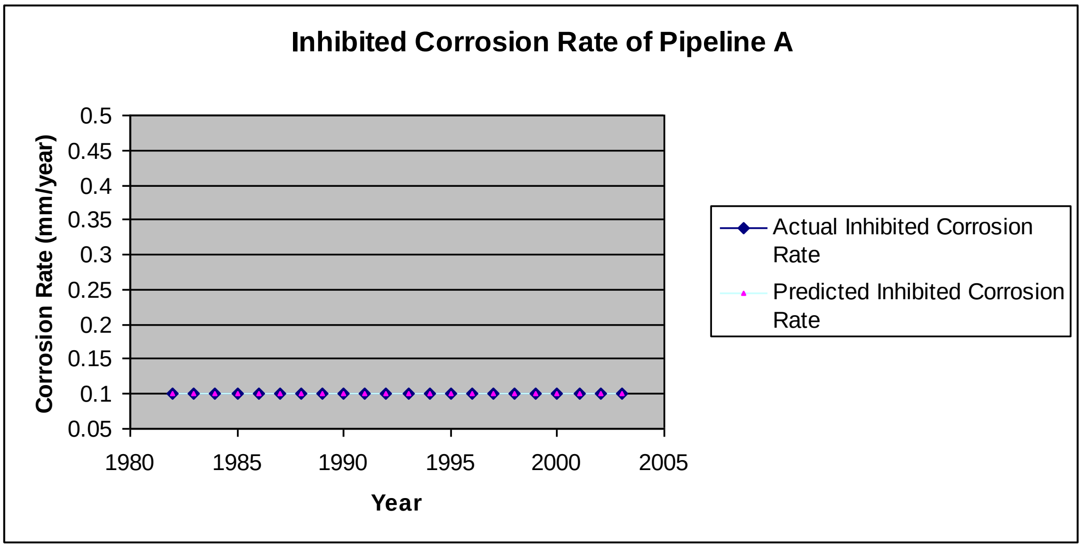


Figure 4.1: Compared between predicted inhibited corrosion rate and actual inhibited corrosion rate of Pipeline A from inspection intelligent pigging data

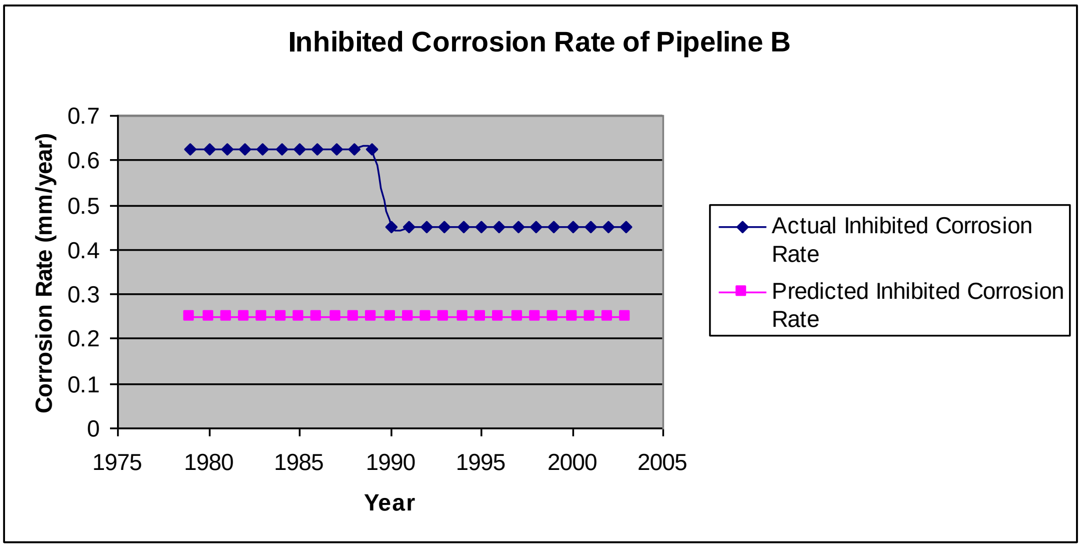


Figure 4.2: Compared between predicted inhibited corrosion rate and actual inhibited corrosion rate of Pipeline B from inspection intelligent pigging data

Figure 4.1 showed that performance of corrosion inhibitor agree with the predicted inhibited corrosion rate. However, Figure 4.12, Pipeline B actual inhibited corrosion rate is not acceptable compare to the predicted inhibited corrosion rate.

Corrosion inhibitor dosage injected into the Pipeline A is 13 L/day base on the effective corrosion inhibitor injection study carried out resulting the corrosion rate of Pipeline A is within the acceptable corrosion rate. However, corrosion inhibitor dosage of 5 L/day is injected into the Pipeline B and resulting higher inhibited corrosion rate compare to the predicted inhibited corrosion rate. The comparison of corrosion inhibitor dosage and inhibited corrosion rate of Pipeline A and B is showed in Figure 4.3.

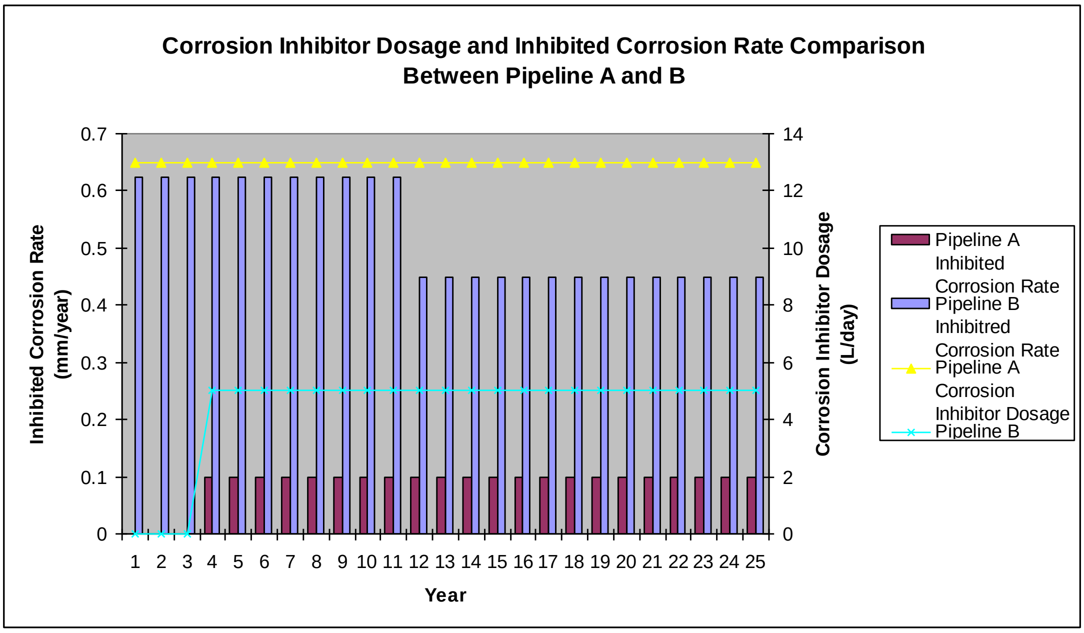


Figure 4.3: Comparison between corrosion inhibitor dosage and inhibited corrosion rate between Pipeline A and Pipeline B

Based on these data, Pipeline A is in good condition. However, Pipeline B has higher inhibited corrosion rate compare to predicted inhibited corrosion rate. This is due to insufficient dosage of corrosion inhibitor injected into the pipeline. This is apparent from the pipeline annual integrity review reported that there is no study done on optimum dosage of corrosion inhibitor for Pipeline B. Pipeline A on the other hand there is study being carried out to obtain the optimum dosage of 13L/day corrosion inhibitor to be injected into the pipeline. The integrity of Pipeline A and Pipeline B is summarized in Table 4.2.

Table 4.2: Integrity Summary for Pipeline A and B

	Pipeline A	Pipeline B
Predicted Corrosion Rate (mm/year)	0.11	0.25
Wall Thickness (mm)	14.3	12.7
Actual Corrosion Rate (mm/year)	Negligible	0.63 and 0.45
Effective Corrosion Inhibitor Injection Study	Yes	No
Corrosion Inhibitor Dosage	13 L/day	5 L/day
Corrosion Inhibitor Injection Method	Continuous	Continuous
Corrosion Inhibitor Availability	High	Low

4.1.1 Field Pipeline Data Discussion

Corrosion inhibitor availability does affect the integrity of the pipelines. High corrosion inhibitor availability in Pipeline A is due to the effective corrosion inhibitor injection study carried out to obtain the optimum dosage of corrosion inhibitor formulation to be injected into the pipeline. Meanwhile, Pipeline B has low corrosion inhibitor availability because there is no study carries out to obtain the formulation of optimum dosage corrosion inhibitor to be injected into the pipeline. Corrosion inhibitor dosage in Pipeline A is higher compare to corrosion inhibitor dosage in Pipeline B. With limited data available, assumption being made that Pipeline B has low corrosion inhibitor availability that causes the pipeline facing severe corrosion rate.

Field data for Pipeline A and B were not sufficient to prove the effect of the corrosion inhibitor availability effect piping integrity because there was no data on the corrosion inhibitor injection dosage into the pipelines to study on the effect of the corrosion inhibitor availability on the pipeline integrity. Thus, data from Bill Hedges, Dominia Paisley and Richard Woolham in their paper title The Corrosion Availability Model using Prudoe Bay as their field pipelines case study [3] as per discussed in the Section 2.4.

With the supporting data from the Prudhoe Bay Flow lines, it showed that corrosion inhibitor dosage injected into the pipelines will determine the corrosion rate of the pipelines. The different corrosion inhibitor dosage injected into the Prudhoe Bay data can be used to justify that severe corrosion on Pipeline B is due to the corrosion inhibitor availability because the corrosion inhibitor dosage injected into Pipeline B is insufficient. Further finding should be carried out in Pipeline B where the corrosion inhibitor dosage injected into the line shall be identified.

4.2 Laboratory Simulation Test Result

Laboratory simulation test result had being divided into 3 sections: (1) Laboratory testing to determine the optimum dosage of corrosion inhibitor, MACE 2204 in 3% NaCl at 40°C and pH5. (2) Laboratory testing on the lower than optimum dosage corrosion inhibitor and (3) Laboratory testing to justify the optimum corrosion dosage inhibitor efficiency. The result of the laboratory test is described in detail in this Section 4.3.

4.2.1 Experiment to Determine Corrosion Inhibitor Optimum Dosage

The optimum dosage that required by the corrosion inhibitor used in the experiment is unknown. The objective of this section experiment is to determine the optimum dosage of corrosion inhibitor needed for the solution at 40°C and pH5.

4.2.1.1 Mild Steel Uninhibited Corrosion Rate

Based on the theory explained in the previous section, the corrosion rate is calculated by the data acquisition system using software called Gill 12 Weld Tester Serial No 1350- Sequencer. The corrosion rate result of the mild steel without adding corrosion inhibitor is shown in Figure 4.4. From the result of the uninhibited corrosion rate of the mild steel is 1.83 mm/year.

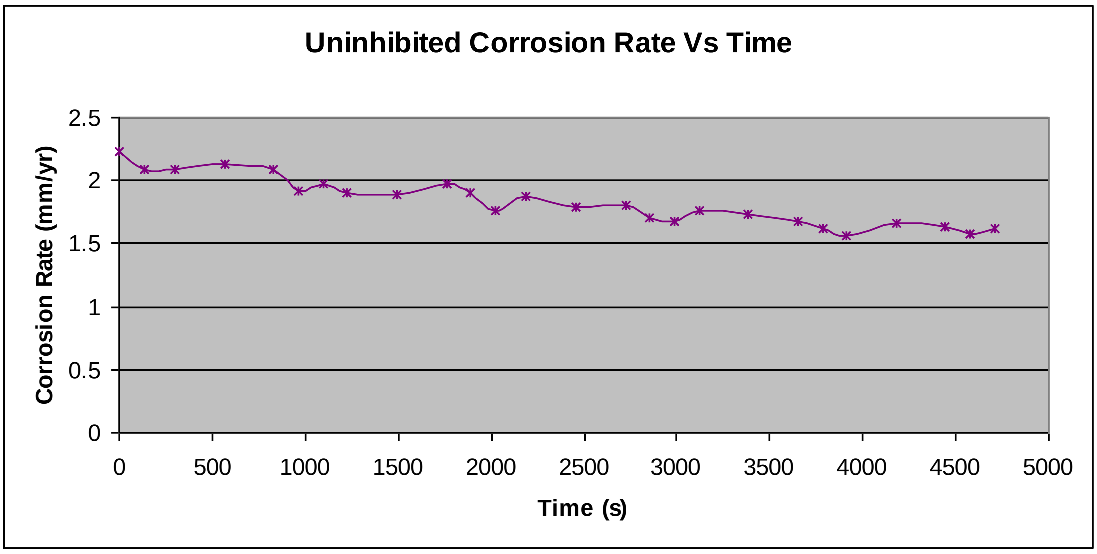


Figure 4.4: Graph plot from the result of the mild steel uninhibited corrosion rate versus time at the temperature of 40°C and pH5.

4.2.1.2 Mild Steel with 40ppm of Corrosion Inhibitor.

The inhibited corrosion rate of 40 ppm dosage of PI is shown in Figure 4.5, where the 40ppm inhibited corrosion rate is plotted against time. The average corrosion rate for the mild steel with 40ppm of corrosion inhibitor is around 1.6 mm/year. From here we can see that the corrosion rate start to crease by 0.264 mm/year. The efficiency of the 40ppm of corrosion inhibitor in 3% NaCl solution is 14.4%.

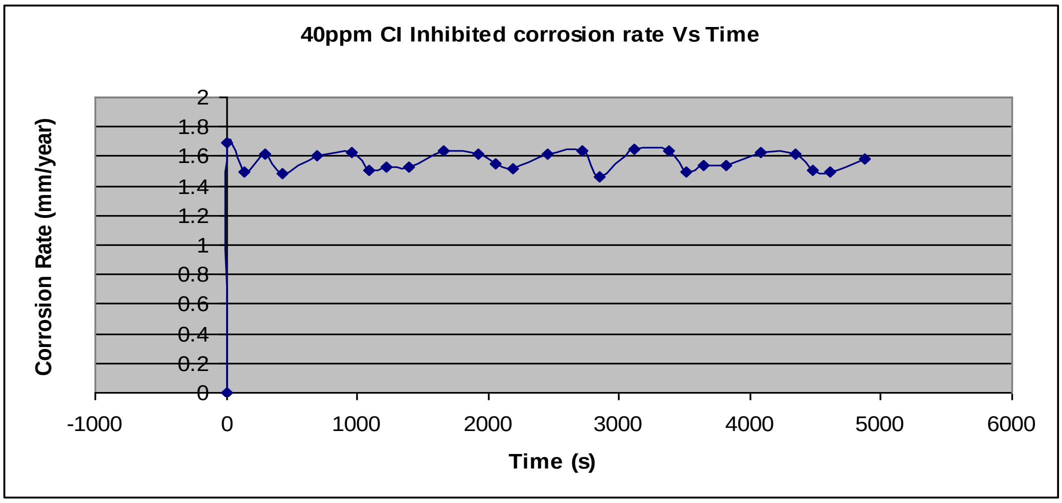


Figure 4.5: Graph plot from the result of inhibited corrosion rate for mild steel with 40ppm corrosion inhibitor at the temperature of 40°C and pH5.

4.2.1.3 Mild Steel with 80ppm Corrosion Inhibitor

Due to the low corrosion rate decrease, the optimum dosage of corrosion inhibitor does not achieve yet. Thus another 40ppm of corrosion inhibitor is added into the solution making the dosage of the corrosion inhibitor in the solution becoming 80ppm. The result of the corrosion rate of this solution is shown in Figure 4.6 below. From the result of the test, we found that the mean inhibited corrosion rate is 1.2 mm/year. With 80ppm of CI in the solution the efficiency of the corrosion inhibitor increases and reduces the corrosion rate of the mild steel. The efficiency of the corrosion inhibitor now is 33.33%.

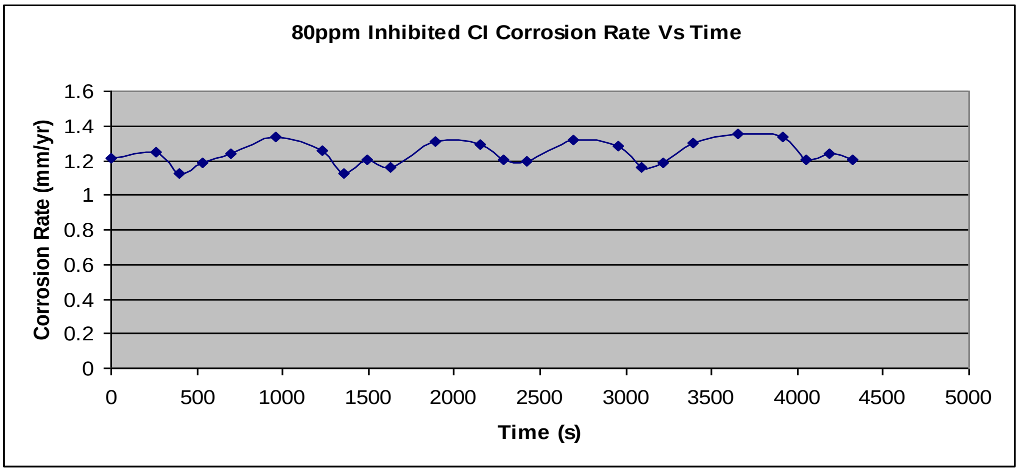


Figure 4.6: Graph plot from the result of inhibited corrosion rate for mild steel with 80ppm corrosion inhibitor at the temperature of 40^oC and pH5.

4.2.1.4 Mild Steel with 120ppm Corrosion Inhibitor

The corrosion rate for 80ppm is still considered very high and the optimum dosage of the corrosion inhibitor in the solution still not yet achieve. Corrosion inhibitor of 20 micro liters is added into the solution to make it 120ppm of corrosion inhibitor in the solution. The result of the corrosion rate of the mild steel in 120ppm corrosion inhibitor of 3% NaCl is shown in Figure 4.7. The mean inhibited corrosion rate of 120ppm CI is 1.2 mm/year. From the dosage of the corrosion inhibitor injected into the system, the corrosion rate suppose to reduce continuously but due to some unknown reason the corrosion rate stop to reduce, and gave the same corrosion rate as the 80ppm corrosion inhibitor corrosion rate.

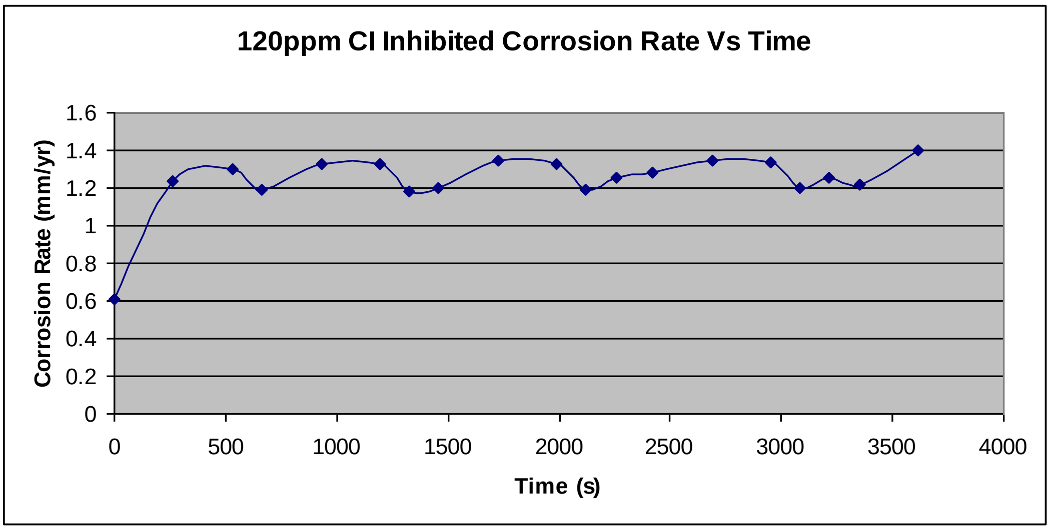


Figure 4.7: Graph plot from the result of inhibited corrosion rate for mild steel with 120ppm corrosion inhibitor at the temperature of 40^oC and pH5.

4.2.1.5 Mild Steel with 320ppm corrosion inhibitor

Another 200 micro liter of corrosion inhibitor is added into the solution to make the solution become 320ppm corrosion inhibitor in 3% NaCl. The result of mild steel corrosion rate in 320ppm corrosion inhibitor is shown in Figure 4.8 and 4.9. In this experiment of 320ppm of corrosion inhibitor in the solution, 2 run had been taken, meaning that for this experiment it had run for approximately 2 hours. The purpose is to make sure the stabilization of the corrosion rate in the 320ppm of corrosion inhibitor in the solution. From the result, the mean inhibited corrosion rate for the first run was 1.2 mm/year and for the second run was 1.2 mm/year.

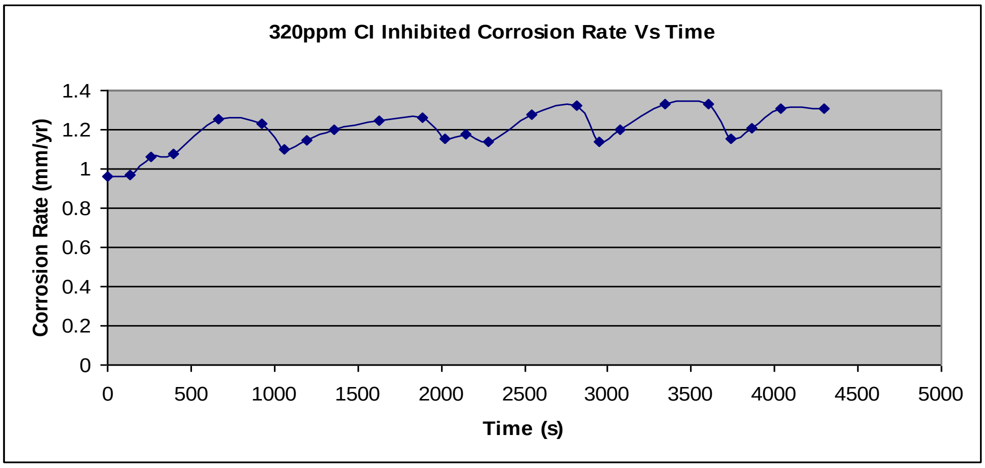


Figure 4.8: Graph plot from the result of inhibited corrosion rate for mild steel with 320ppm corrosion inhibitor at the temperature of 40°C and pH5.

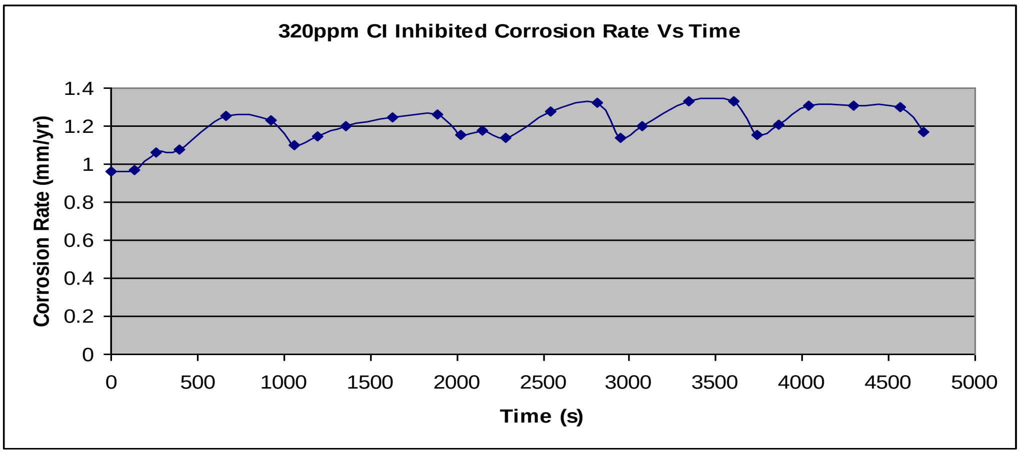


Figure 4.9: Graph plot from the result of inhibited corrosion rate for mild steel with 320ppm corrosion inhibitor in the second run experiment at the temperature of 40°C and pH5.

4.2.1.6 Mild Steel with 1320ppm Corrosion Inhibitor

Due to no changes in the corrosion rate after adding 320ppm of corrosion inhibitor, it is believe that the corrosion inhibitor had reached the optimum performance for the solution prepared in the laboratory. In order to justify the statement above, the corrosion inhibitor of 1ml is added into the solution to make the corrosion inhibitor 1320ppm in the solution. The result of the corrosion rate with 1320ppm corrosion inhibitor is shown in Figure 4.10. From the result, the mean inhibited corrosion rate of 1320ppm is 1.2 mm/year.

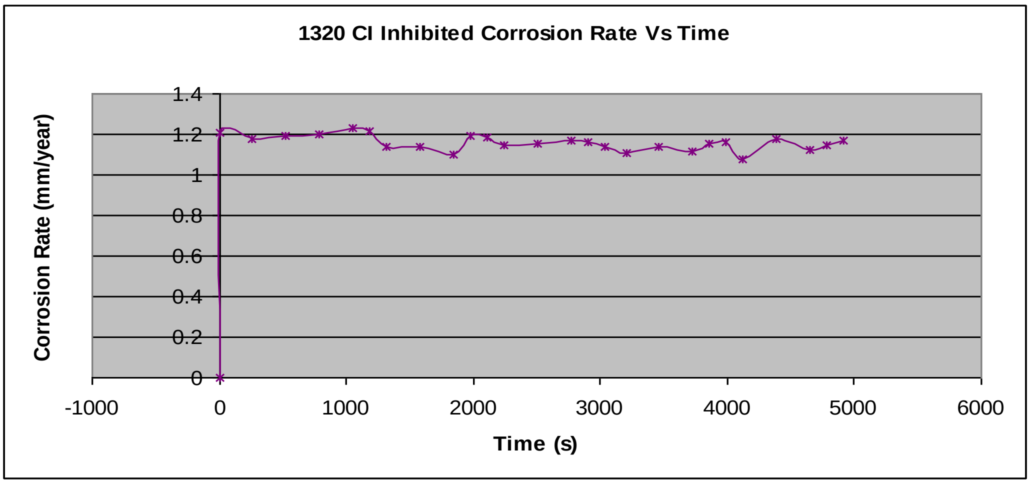


Figure 4.10: Graph plot from the result of inhibited corrosion rate for mild steel with 1320ppm corrosion inhibitor at the temperature of 40°C and pH5.

4.2.1.7 Corrosion Inhibitor Optimum Dosage Determination: Discussion

The bubble static testing is done using linear polarization resistance method to measure the corrosion rate of the mild steel using different dosage of corrosion inhibitor. The testing had being carried out in series, each of the different dosage has the test duration of one hour to get the most accurate corrosion rate result. The first section of this laboratory experiment is to determine the optimum dosage of the corrosion inhibitor needed in 3% NaCl at temperature 40°C and pH5, in order to study the effect of corrosion inhibitor availability (in this case is the dosage of the corrosion inhibitor) on the corrosion rate.

The experiment started with mild steel in the solution without injecting corrosion inhibitor. 40 µL of corrosion inhibitor into the solution after one hour of inhibited corrosion rate obtain, 40ppm is selected base on the reference from the BP Round

Robin validation of test method [1]. Then continue with increasing dosage of corrosion inhibitor.

From the result of 40ppm inhibited corrosion rate obtain, the efficiency was still low, 14.4%, thus another 40 µL of corrosion inhibitor is added in to obtain 80ppm of corrosion inhibitor in the solution. The 80ppm inhibited corrosion rate has the efficiency of 32.57%. Another 40 µL of corrosion inhibitor is added in to obtain 120ppm of corrosion inhibitor in the solution to achieve higher efficiency of the inhibited corrosion rate. But the result of 120ppm inhibited corrosion rate is the same as the 80ppm inhibited corrosion rate. In order to justify that the corrosion inhibitor of 120ppm dosage could not reduce the corrosion rate after reaching 1.2mm/year, 200µL of corrosion inhibitor is added into the solution to obtain 320ppm corrosion inhibitor in the solution. The result of the 320ppm inhibited corrosion rate still shows the same corrosion rate of 1.2 mm/year. Second run of linear polarization resistance measurement on the 320ppm also shown that the corrosion rate still remain the same. 1000 µL of corrosion inhibitor is added into the solution to produce 1320ppm corrosion inhibitor in the solution also tested for the inhibited corrosion rate, and the result still does not show any significant changes. Thus, from this section of experiment the optimum corrosion inhibitor dosage is 80ppm and the efficiency of the corrosion inhibitor in 3% NaCl at temperature 40oC and pH 5 is 32.57%.

From this experiment we will consider that the optimum dosage of corrosion inhibitor in the laboratory experiment solution is 80ppm, the most optimum efficiency of the corrosion inhibitor is 33.33%, meaning that the corrosion inhibitor no matter add in how much in the solution will give the maximum reduction in the corrosion rate is around 33.33% compare to uninhibited corrosion rate.

The result to show the relationship of the corrosion inhibitor availability and the corrosion rate of the mild steel is shown in Figure 4.12.

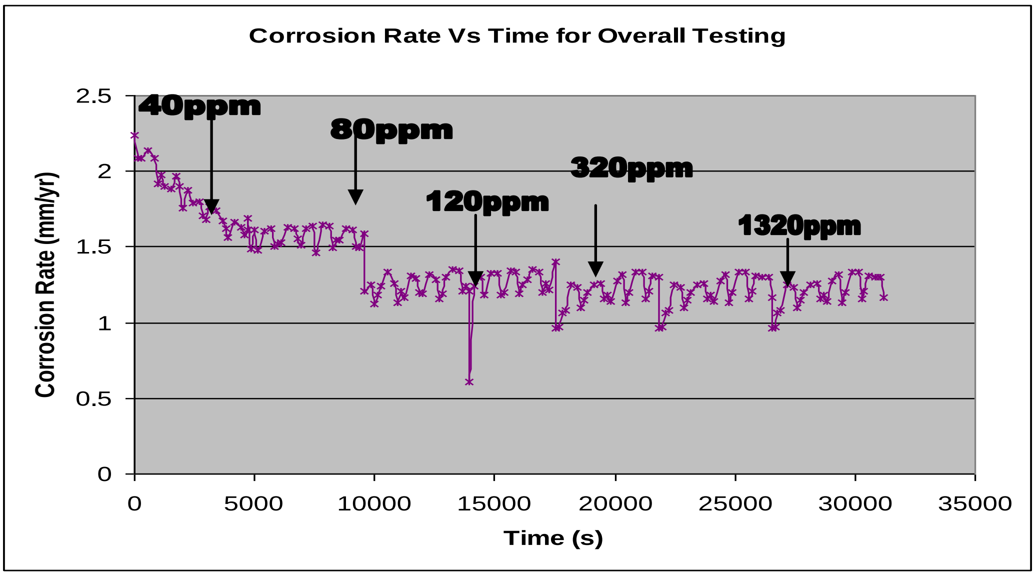


Figure 4.11: Overall dosage corrosion inhibitor and their corrosion rate of the mild steel at the temperature of 40°C and pH5.

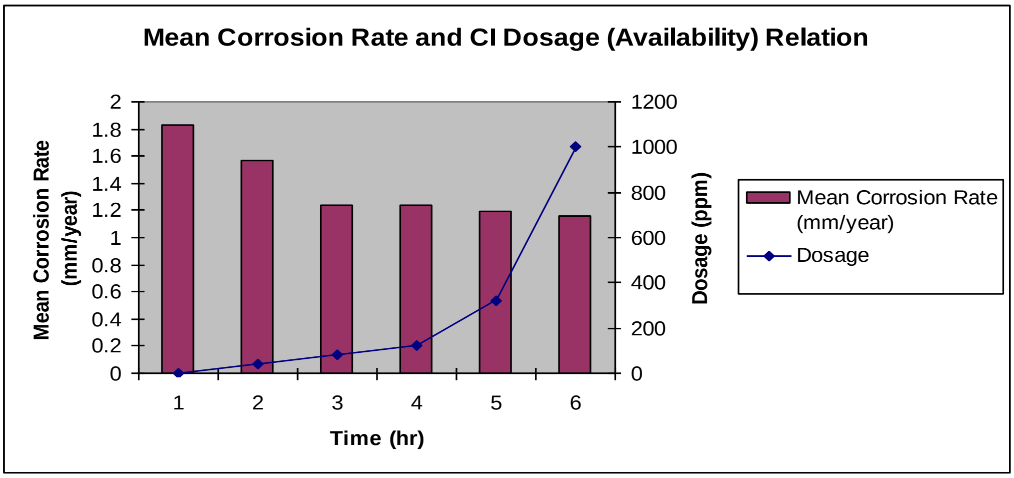


Figure 4.12: Relationship between mean corrosion rate of the mild steel and corrosion inhibitor availability at the temperature of 40°C and pH5.

4.2.1 Experiment of Low Corrosion Inhibitor Availability

The optimum corrosion inhibitor dosage is found to be 80ppm from the previous section of experiment. In order to justify low corrosion availability will cause increase in corrosion rate. Experiment with corrosion inhibitor dosage less than 80ppm is carried out. The result and discussion of each dosage is stated in the following sections.

4.2.2.1 Mild Steel with 20ppm Corrosion Inhibitor

From the previous section experiment the optimum corrosion inhibitor dosage is 80ppm, thus in order to study the effect of the low corrosion inhibitor availability the 20ppm of corrosion inhibitor is injected into the solution, this situation equivalent to corrosion inhibitor availability of 25% base on the optimum dosage required by the solution. The inhibited corrosion rate of the 20ppm corrosion inhibitor plotted against time is shown in Figure 4.13 below. From the result, the mean inhibited corrosion rate is 1.8 mm/year. There is not much changes in the corrosion rate compare to the uninhibited corrosion rate obtain from the section 4.4.2.1.

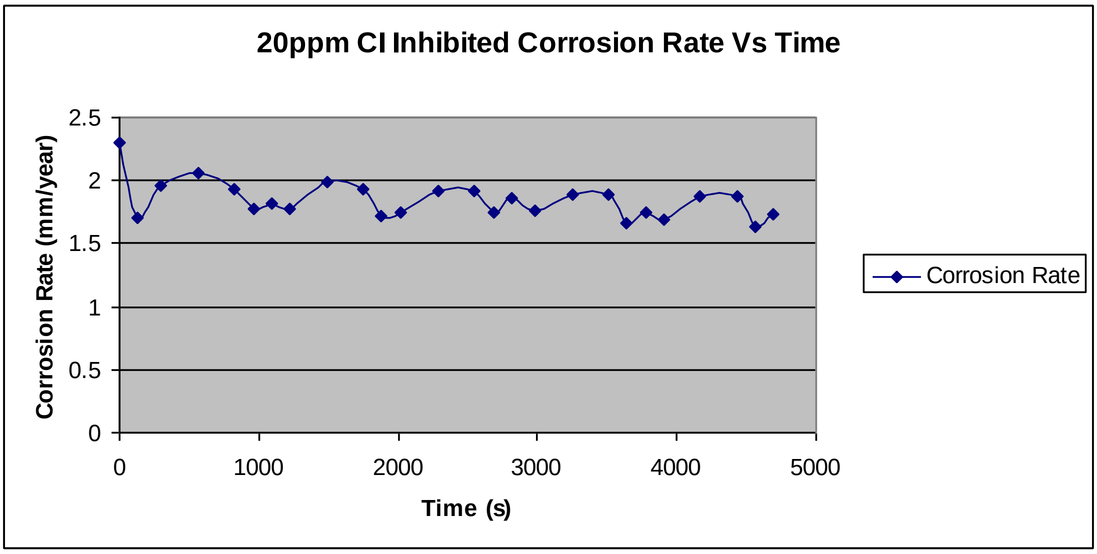


Figure 4.13: Graph plot from the result of inhibited corrosion rate for mild steel with 20ppm corrosion inhibitor at the temperature of 40^oC and pH5.

4.2.2.2 Mild Steel with 30ppm Corrosion Inhibitor

Another 10µL of corrosion inhibitor is added into the previous solution of 20ppm corrosion inhibitor to make it 30ppm corrosion inhibitor solution. The 30ppm corrosion inhibitor dosage is equivalent to corrosion inhibitor availability of 37.5%. The inhibited corrosion rate due to the corrosion inhibitor availability in this case is plotted against time shown in Figure 4.14. The mean inhibited corrosion rate of 37.5% availability is 1.6 mm/year. The 37.5% corrosion inhibitor availability inhibited corrosion rate has the efficiency of 12.9%.

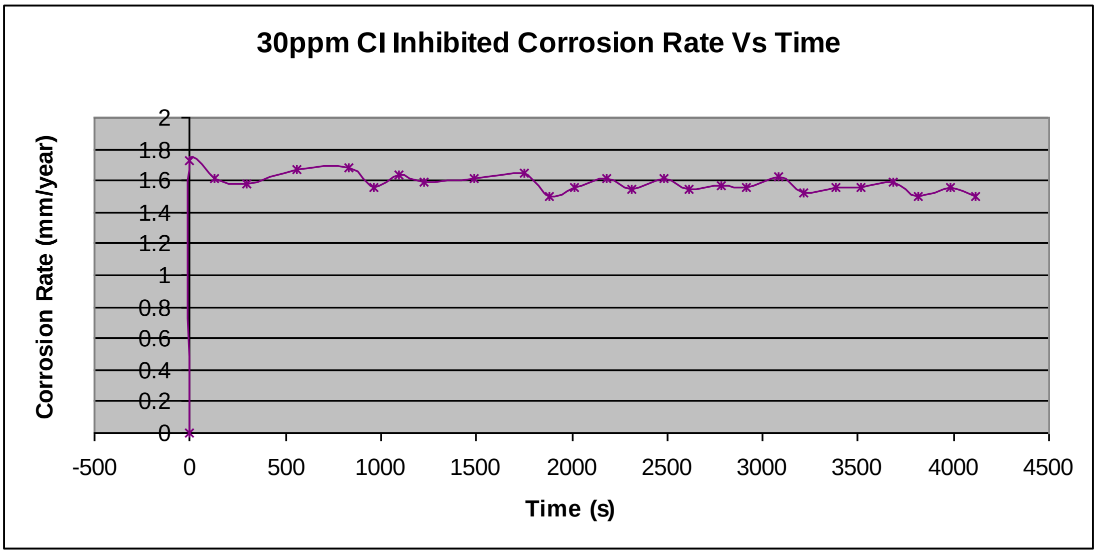


Figure 4.14: Graph plot from the result of inhibited corrosion rate for mild steel with 30ppm corrosion inhibitor at the temperature of 40°C and pH5.

4.2.2.3 Mild Steel with 50ppm Corrosion Inhibitor

Another 20µL of corrosion inhibitor is added into the previous solution of 20ppm corrosion inhibitor to make it 50ppm corrosion inhibitor solution. The 50ppm corrosion inhibitor dosage is equivalent to corrosion inhibitor availability of 62.5%. The inhibited corrosion rate due to the corrosion inhibitor availability in this case is plotted against time shown in Figure 4.15. The mean inhibited corrosion rate of 62.5% availability is 1.55 mm/year. The 62.5% corrosion inhibitor availability inhibited corrosion rate has the efficiency of 15.4%.

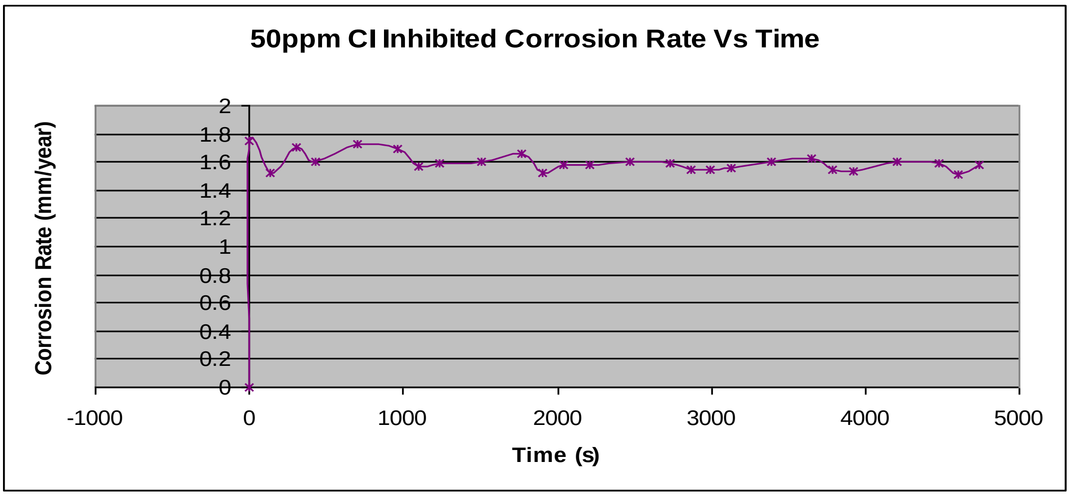


Figure 4.15: Graph plot from the result of inhibited corrosion rate for mild steel with 50ppm corrosion inhibitor at the temperature of 40°C and pH5.

4.2.3 Experiment to Verify Optimum Corrosion Inhibitor Dosage

One simple experiment is carried out again with the corrosion inhibitor dosage of 80ppm, the purpose of this experiment is to re-justify the optimum corrosion inhibitor dosage for the experiment carried out in the laboratory for solution 3% NaCl, at temperature 40^{o}C and pH5. The result of the inhibited corrosion rate is shown in Figure 4.16. The mean inhibited corrosion rate for this case is 1.3 mm/year. Compare to the corrosion rate obtain at the first section of the experiment, it is acceptable.

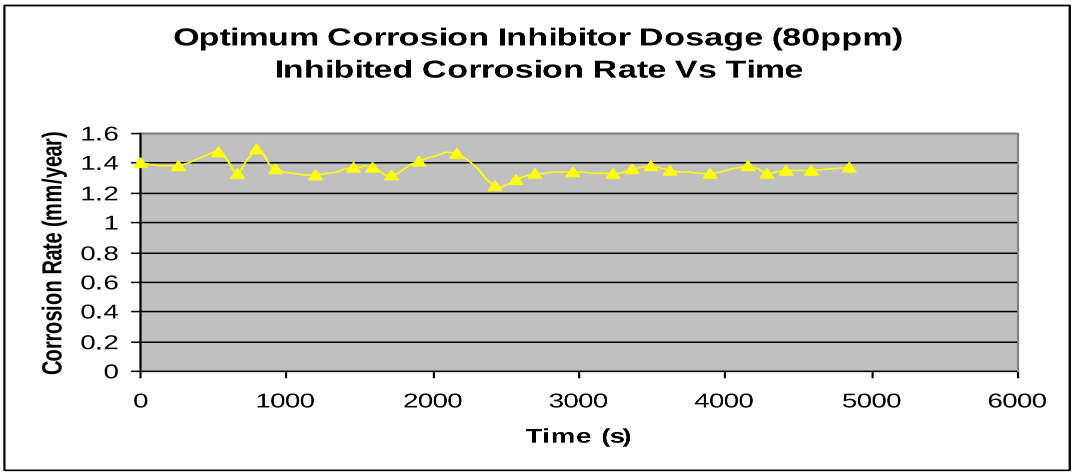


Figure 4.16: Graph plot from the result of inhibited corrosion rate for mild steel with 80ppm corrosion inhibitor at the temperature of 40^{o}C and pH5.

4.3 Laboratory Testing Discussion

The efficiency of the corrosion inhibitor is only 33.33% at the experiment condition whereby actual field corrosion inhibitor has the efficiency of 95%. In this laboratory simulation, corrosion inhibitor availability will be taken into account to study the dosage of corrosion inhibitor dosage (availability) effect on the corrosion rate. Below the optimum corrosion inhibitor dosage will be consider as low corrosion inhibitor availability.

The dosage of 80ppm of corrosion inhibitor is the optimum dosage corrosion inhibitor injected into solution can be achieved in this laboratory experiment. Dosage less than 80ppm of corrosion inhibitor will give a higher corrosion rate, this has been shown in the second section of the laboratory experiment where corrosion inhibitor is injected into the solution at the lower than 80ppm to simulate the condition where corrosion availability low in the system. For examples 20ppm of corrosion inhibitor, the corrosion rate difference is around 90% from the reduction that can be achieved in the optimum dosage, the difference of decrease in corrosion rate compare to the optimum dosage start to increase as the corrosion inhibitor dosage increase. 30ppm of corrosion inhibitor has the difference of 66.66% reduction in corrosion rate compare to the optimum dosage of corrosion inhibitor, followed by 40ppm with 50% of difference reduction in corrosion rate achieved by the optimum dosage, and 50ppm corrosion inhibitor dosage gave 47.1% difference reduction in corrosion rate compare to the optimum corrosion inhibitor dosage corrosion rate.

There will be over design if additional corrosion inhibitor dosage injected into the solution. For example in the 320ppm corrosion inhibitor in the solution, the corrosion rate does not decrease although the corrosion inhibitor added into the solution in large volume. To strengthen the justification of the corrosion inhibitor optimum dosage is at 80ppm, a solution of additional 1000ppm of corrosion inhibitor added into the solution, the corrosion rate of the mild steel still around the corrosion rate of the 80ppm corrosion inhibitor. From this result, we can say that corrosion rate cannot be reduced by just adding extra dosage of corrosion inhibitor after it has exceeded the optimum dosage. The relationship between the corrosion inhibitor availability (dosage) is shown in Figure 4.17.

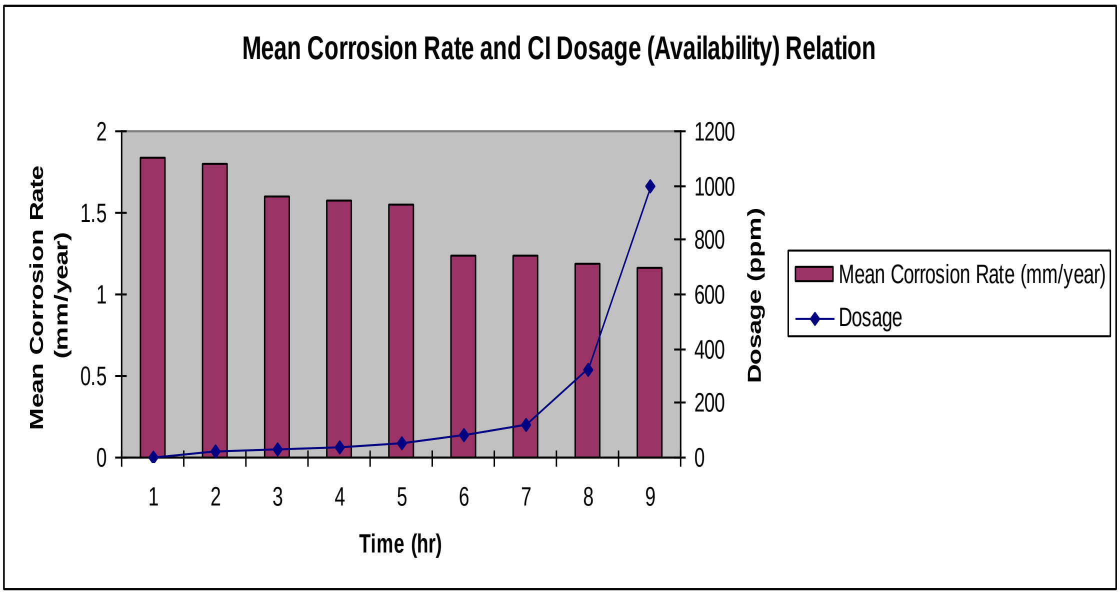


Figure 4.17: Relationship of corrosion inhibitor availability (dosage) with the corrosion rate

The laboratory testing summary result is shown in Table 4.3. The results show that corrosion inhibitor availability effect on the efficiency of the corrosion inhibitor and affecting the service life of the sample. The service life corrosion for the sample is taken as 6 mm.

Table 4.3: Summary of the Laboratory Test and Interpretation

Availability (%)	Corrosion Inhibitor ppm	CR (mm/year)	Efficiency (%)	Service Life (years)	Ideal Case	Ideal Efficiency (%)	Ideal CR (mm/year)	Ideal Service Life (Years)
25	20	1.8	1.64	3.33		4.67	1.74	3.4
37.5	30	1.6	14.4	3.75		41.1	1.08	5.6
50	40	1.6	14.4	3.75		41.1	1.08	5.6
62.5	50	1.55	15.4	3.8		43.9	1.02	5.9
100	80	1.2	33.33	5		95	0.0915	65.6
-	120	1.2	33.33	5		95	0.0915	65.6
-	320	1.2	33.33	5		95	0.0915	65.6

Ideal case is when corrosion inhibitor is assumed behave in the optimum state, where the corrosion efficiency is 95% at the optimum dosage. From the laboratory test result, the corrosion inhibitor availability does not show much effect on the service life, but in the field most of the corrosion inhibitor is tested to have efficiency of 95% before it is used in the field. Assumption had being made in this laboratory experiment where is the efficiency of 33.33% is assume to give the optimum efficiency of 95%, and using linear interpolation to calculate the service life of the low corrosion inhibitor availability samples. The effect of corrosion inhibitor availability does have a big impact on the service life in the ideal case, the service life reduce tremendously in low corrosion inhibitor availability. The corrosion inhibitor availability effect on the service life is shown in Figure 4.18 and 4.19.

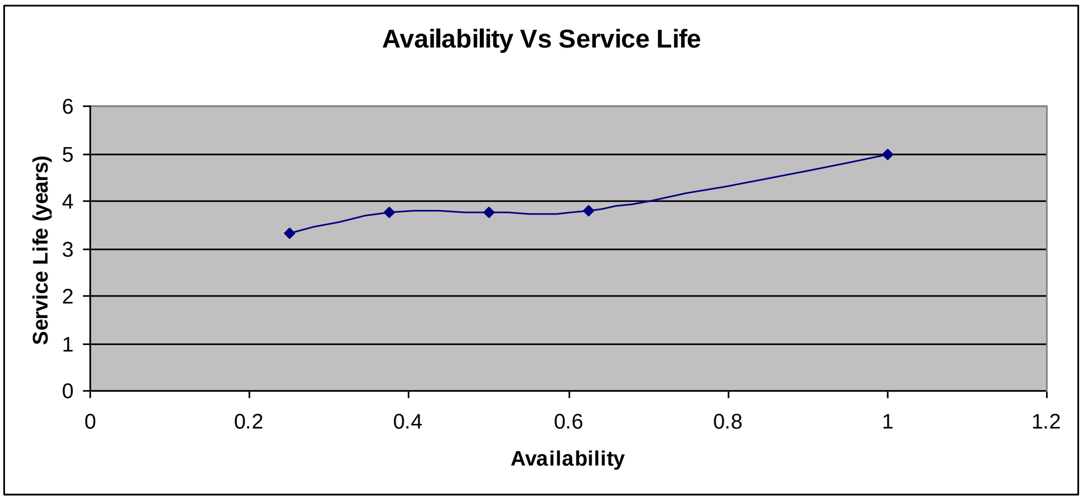


Figure 4.18: Relationship between corrosion inhibitor availability and service life base on laboratory result sample

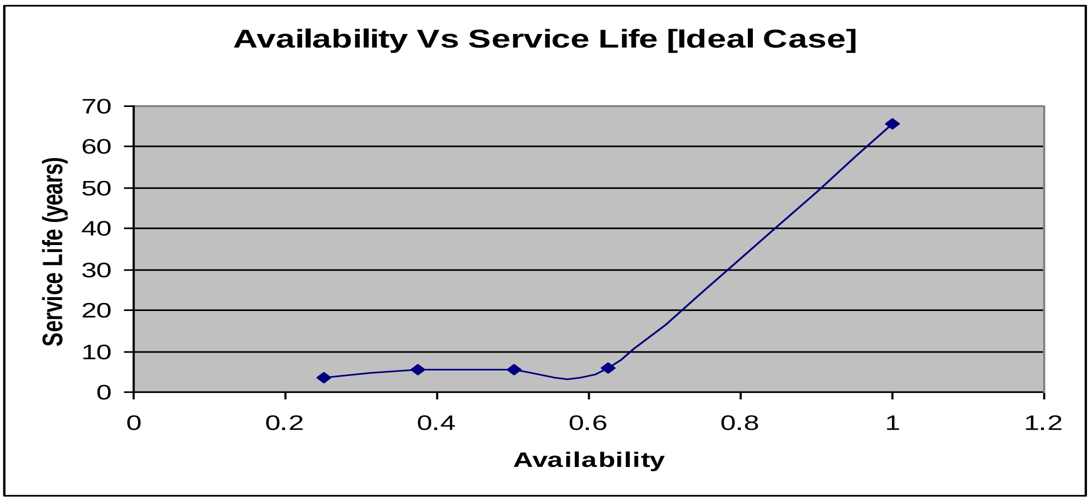


Figure 4.19: Relationship between corrosion inhibitor availability and service life base on the laboratory result in the ideal case, where corrosion inhibitor efficiency is 95% at optimum dosage.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This project is initiated from the collaborate on with PETRONAS Carigali Sdn Bhd, Material & Corrosion Facilities Engineering Department. Field data gathered from the collaborating company showed that Pipeline A had no severe corrosion problem while Pipeline B faced severe corrosion problem. Based on limited field data, the possibility of the severe corrosion in the Pipeline B is due to the low corrosion availability causes from the insufficient dosage of the corrosion inhibitor.

Based on laboratory experiments, corrosion inhibitor availability is crucial to ensure the target inhibited corrosion rate is achieved. Low corrosion inhibitor availability decreases the service life of the pipeline significantly. However, over injection of corrosion inhibitor does not improve the service life of the pipelines. Corrosion inhibitor availability cannot compensate the service life reduction due to previous uninhibited events by overdosing of corrosion inhibitor. Thus, serious effort must be taken to ensure corrosion inhibitor is at the design corrosion inhibitor availability.

5.2 Recommendation

This project is collaborated with PETRONAS Carigali, personal recommendation is that student will be given more priority to access to the field data. Future work base on the field case study should focus more on the corrosion inhibitor dosage that injected into the pipeline in a range of longer period of time, 10 to 20 years to have a better comparison. Uninhibited events data shall be collect from the field as well.

Recommendation for laboratory experiment to study on corrosion inhibitor availability shall be done using rotating cylinder electrode (RCE) instead of using static bubble test alone. This is because static bubble test does not simulate the real situation in the pipeline due to the low shear wall stress provided by the static bubble test. Linear polarization resistance measurement alone do sufficient for the monitoring of the corrosion rate in the laboratory experiments, but for more reliable data weight loss method also can be used to determine the corrosion rate of the test.

Laboratory experiment shall be conducted with the collaboration with corrosion inhibitor provider company, for example MACES Sdn Bhd, so that student will be able to obtain confidential data such as experiments that had being conducted in the collaborating company laboratory and exact compositions that used in the corrosion inhibitor. This will provide more constraint of study area for the student instead of carried out more experiments in order to obtain some data that already available in the corrosion inhibitor provider company.

REFERENCES

[1] A J McMahon, S Webster, "Round Robin Validation of Test Methods", *Corrosion Inhibitor Test Method, Sunbury Report No. ESR 95 ER.054 dated Nov. 1995.*

[2] A J McMahon, R M Gourdin, "Bubble Test Protocol", *Corrosion Inhibitor Test Method, Sunbury Report No. ESR 95 ER.054 dated Nov. 1995.*

[3] ASTM, Designation: G59-97, "Standard Test Method for Conducting Potentiodynamic Polarization Resistance Measurement", *Annual Book of ASTM Standard.*

[4] Bill Hedges, Dominia Paisley and Richard Woolham, "The Corrosion Availability Model," *Corrosion 2000, Paper 34, NACE International.*

[5] B.R. Linter, G.T. Burstein, "Reactions of pipeline steels in carbon dioxide solutions", *22 June 1998.*

[6] Cintarajan, 24th April 2007, <http://cr4.globalspec.com/thread/7059/Material-Properties-of-EN-8-and-EN-24>

[7] D.A. Lopez, T. Perez and S.N. Simison, "The influence of microstructure and chemical composition of carbon and low alloy steels in CO_2 corrosion. A state-of-the-art appraisal" *Material and Design 24(2003)*

[8] Guoan Zhang, Changfeng Chena, Minxu Lub, Chengwen Chai, Yinshun Wu, "Evaluation of inhibition efficiency of an imidazoline derivative in CO_2-containing aqueous solution", *Science Direct, published 29th April 2007.*

[9] Ian Rippon, 2001, "Carbon Steel Pipeline Corrosion Engineering: Life Cycle Approach," *Corrosion 2001 paper 01055, NACE International*

[10] J.W Palmer, "Corrosion Control by Film Forming Inhibitor", *Corrosion 2000, Paper 06119, NACE International.*

[11] M.B. Kermani and A. Morshed, 2003, "Carbon Diosxide Corrosion in Oil and Gas Production," *A Compendium, Corrosion Vol. 59, No. 8, NACE International*

[12] PETRONAS Technical Standards Design and Engineering Practice, Manual, 2005, "Selection of Material for Life Cycle Performance (EP)," *PTS 39.01.10.11,*

[13] PETRONAS Technical Standards Design and Engineering Practice, Manual, 2003, "Chemical Injection Facilities," *PTS 31.01.10.10*.

[14] S. Nesic, K.-L.J. Lee, "Corrosion Science Section, A Mechanistic Model for Carbon Dioxide Corrosion of Mild Steel in the Presence of Protective Iron Carbonate Film", *Part3: Film Growth Model, Corrosion July 2003*

[15] S Webster, A J McMahon, D M E Paisley, D Harrop, "Corrosion Inhibitor Selection Strategy for Oil Field Pipelines", *Corrosion Inhibitor Test Methods*

[16] William D. Callister, Jr., "Material Science and Engineering An Introduction," *6th Edition, Wiley.*

APPENDIXES

Table A1: Criteria for chemical injection system to meet specified system availability adopted from PTS.

Item	Availability, f		
	Good (f = 0.95)	Excellent (f = 0.99)	Critical (f > 0.99)
Inhibitor demonstrated as suitable for the application	Required	Required	Required
Inhibitor injection pumps	Standard	High reliability	High reliability
Back up pumps	Not required	Required	Required
Check that pump is operating	Daily, manual check	Automated alarm	Automated alarm
Pump planned maintenance	Annual	Annual	May be required more often
Inhibitor tank levels	Daily manual check	Automated alarm	Automated alarm
Report on inhibitor used (or report on compliance with key performance indicators) to responsible corrosion engineer	Monthly	Weekly	Daily
Quarterly manual check on pump injection rate, calibration check on meters	Required	Required	Required
Low or no flow alarm (out of specification, differential pressure across a critical component, or inline flow meters)	Not required	Required	Required
Liquid samples for analysis of residual inhibitor levels and water chemistry	Monthly	Monthly	May be required more often
Corrosion monitoring system response	At least annual manual measurement	Online ER probes; response time 1 day to 7 days	Online fast response monitoring systems; response time 1 hour to 24 hours
Comprehensive review of uninhibited events	Desirable	Required	Required
Persistency taken into account	Not required	Not required	Required
Allowed days inhibitor system downtime per year	18	4	0 to 4
Shut in if inhibition system goes down for greater than the allowed period of time	Effectively never an issue	Possibly	Required
Identify operations technician with responsibility for the inhibition injection system	Required	Required	Required
Corrosion engineering involvement	Monthly review	Weekly review	Daily review
Key Performance Indicators set for operations technicians and corrosion engineers	Required	Required	Required

Table A2: Corrosion Inhibitor Risk Categories

Category	Maximum Required Availability	Maximum Expected Uninhibited Corrosion Rate (mm/y)	Comment	Possible Category Name
1	0%	0.4	Benign fluids where corrosion inhibitor usage is not anticipated (dry gas, stabilised crude oil). Predicted metal loss can be accommodated by corrosion allowance alone.	Benign
2	50%	0.7	Corrosion inhibitor will probably be required but at the expected corrosion rates there will be time to review the need for inhibition based on inspection data.	Low
3	90%	3	Corrosion inhibition will be required for the majority of the field life but the facilities need not be available from day 1.	Medium
4	95%	6	Inhibition is relied on heavily and will be required for the lifetime of the operation. Inhibitor must be available from day 1 to ensure success of the inhibition programme.	High
5	>95%	>6	Carbon steel and inhibition is unlikely to provide integrity for the full field life. Select corrosion resistant materials or plan for repairs & replacements.	Unacceptable

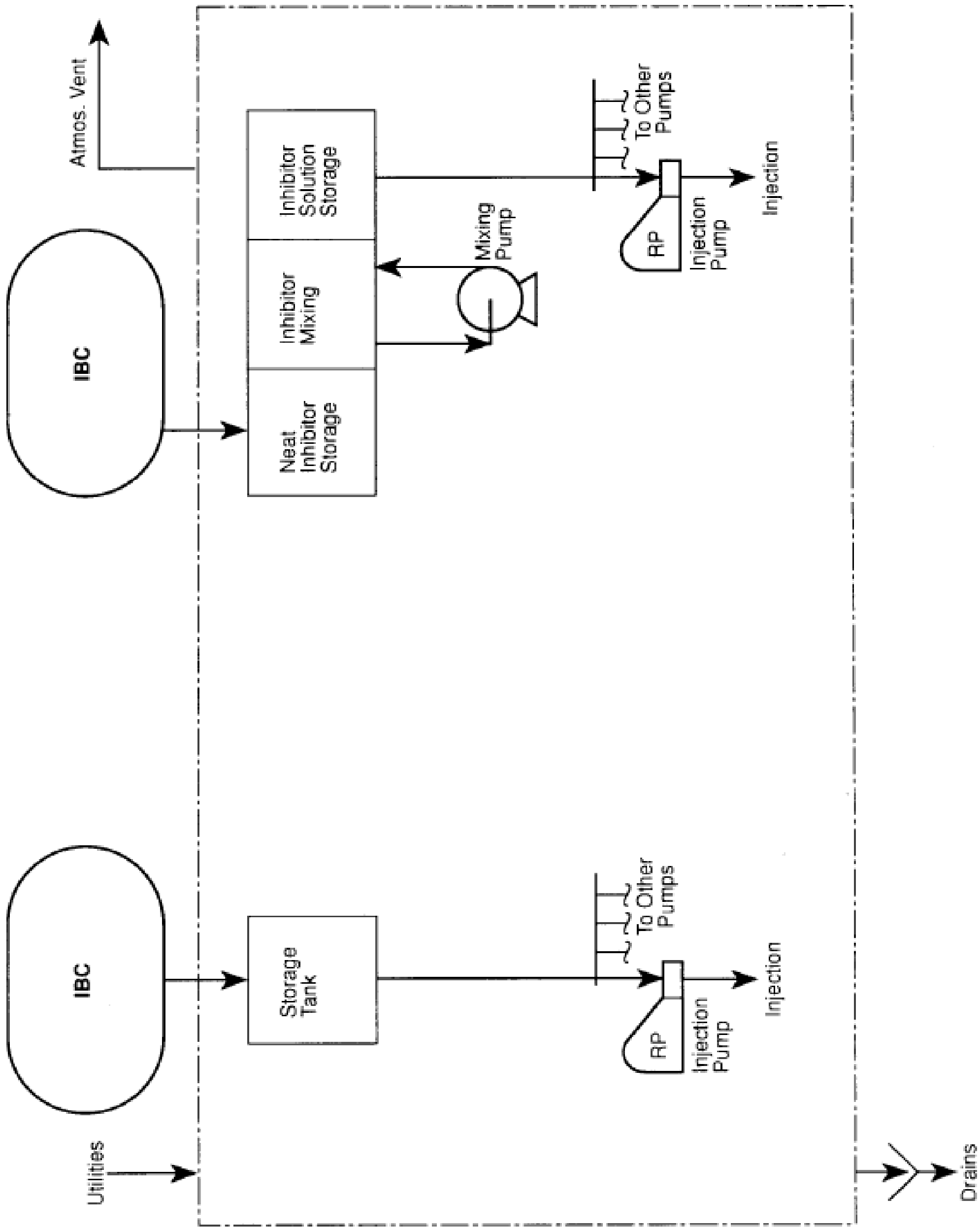


Figure A1: Types of storage and injection system of corrosion inhibitors.

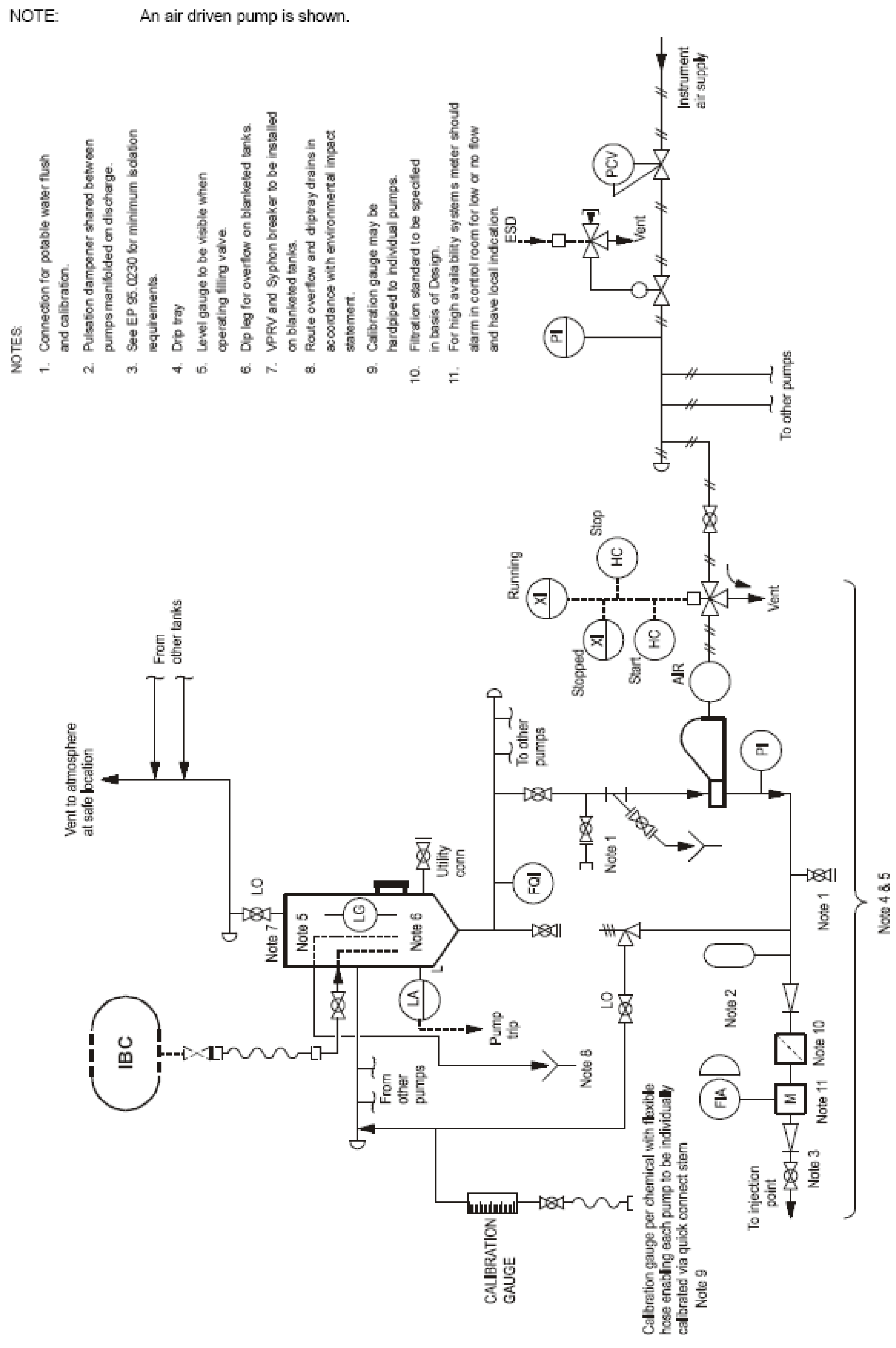
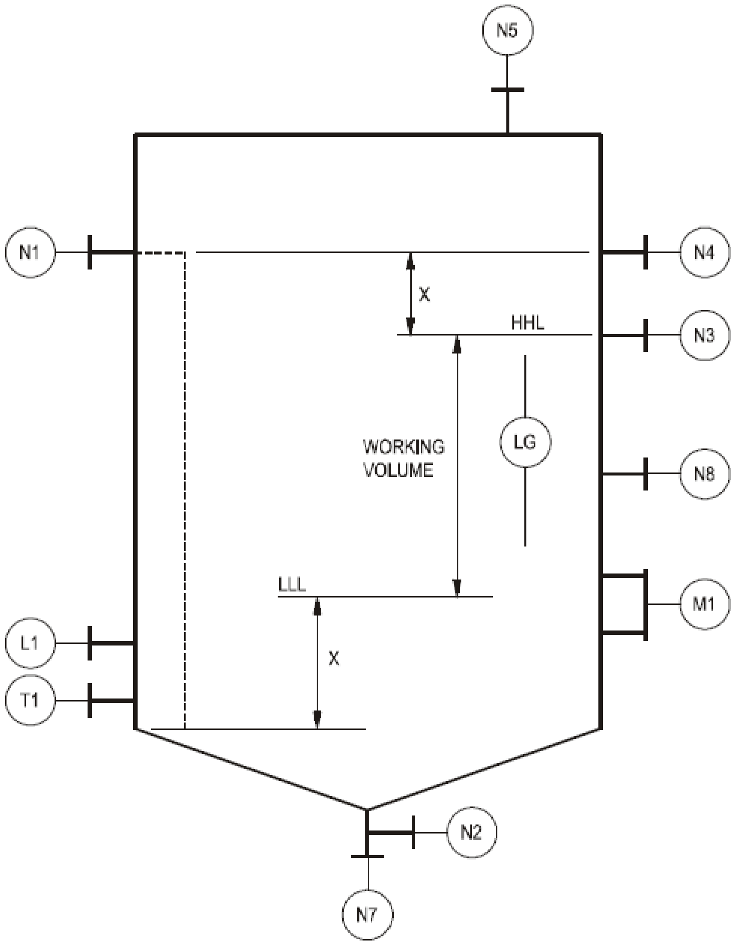


Figure A2: Typical P&ID for storage and injection system of undiluted liquid (no mixing) via an air or electric driven pump.



NOZZLE	DUTY	SIZE	RATING/FACING	
N1	INLET	50 mm (2")	150lb RF	
N2	OUTLET	75 mm (3")	150lb RF	
N3	RELIEF RETURN	50 mm (2")	150lb RF	
N4	OVERFLOW	75 mm (3")	150lb RF	(NOTE 1)
N5	VENT	75 mm (3")	150lb RF	
N7	DRAIN	50 mm (2")	150lb RF	
N8	UTILITY CONNECTION	50 mm (2")	150lb RF	
T1	IMMERSION HEATER	AS REQUIRED BY SERVICE		
M1	MANWAY	600 mm (24")	150lb RF	
L1	LEVEL ALARM	50 mm (2")	150lb RF	

NOTES:

1. Relief return (N3) and overflow (N4) may have internal flange (150lb RF) to permit connection of dip leg.
2. Dimension X to be confirmed per application.

Figure A3: Typical main chemicals injection package storage vessel.

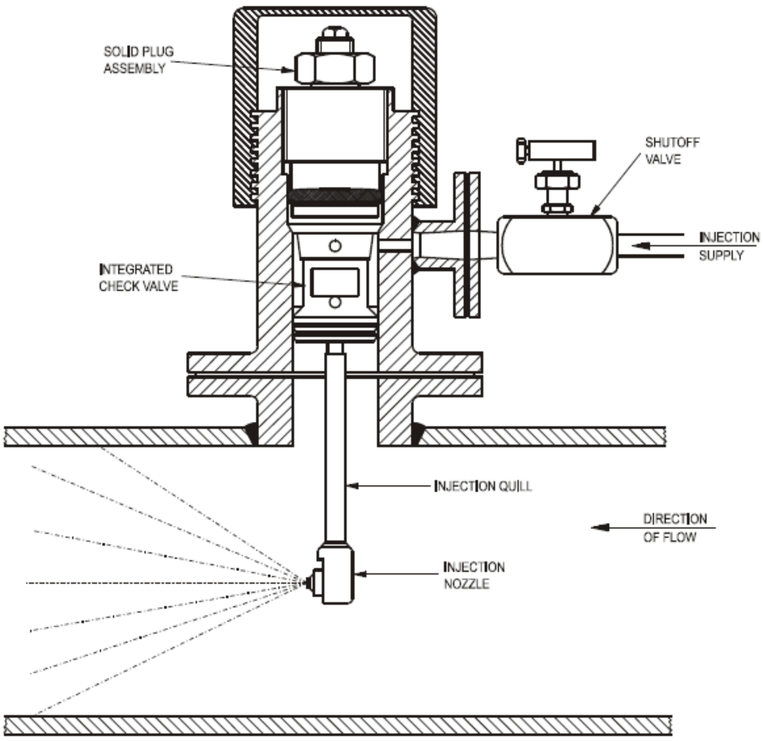


Figure A4: Typical chemical injection quill into gas lines

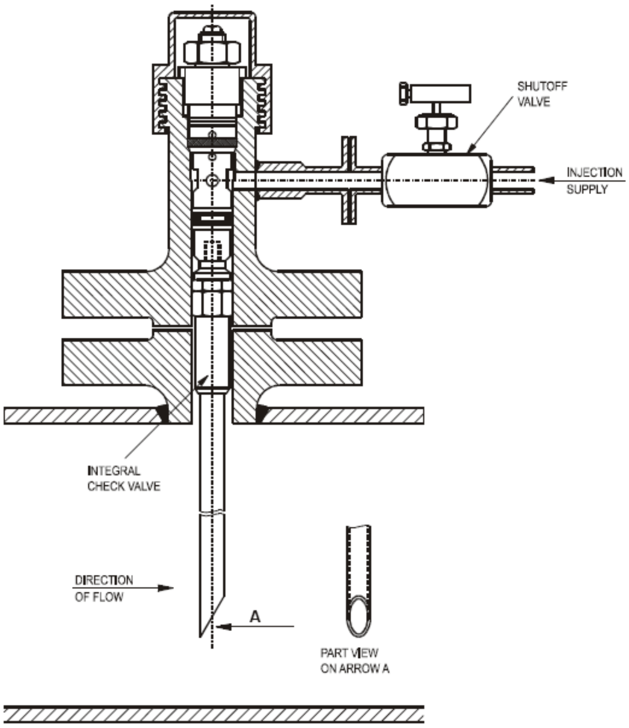


Figure A5: Typical chemical injection quill into liquid lines.

APPENDIX B

Linear Polarization Resistance Result

Laboratory Testing 1:

To Determine Optimum Dosage of Corrosion Inhibitor

Table B1: LPR Result for Uninhibited Corrosion Rate

Time (Sec)	LPR (ohm.cm²)	Icorr (mA/cm²)	Corrosion Rate (mm/year)	Total metal loss (mm)	Potential (mV)
0	135.29	0.1928085	2.2346	0	-673.91
132.17	145.06	0.1798267	2.0841	8.96E-06	-674.49
300.42	144.75	0.1802155	2.0886	2.04E-05	-674.09
565.15	141.71	0.1840865	2.1335	3.87E-05	-673.55
830.15	144.72	0.1802537	2.0891	5.67E-05	-673.57
962.78	157.61	0.1655103	1.9182	6.50E-05	-674.55
1094.9	153.09	0.1703931	1.9748	7.35E-05	-674.06
1227.5	159.1	0.1639613	1.9003	8.17E-05	-674.39
1493.2	160.56	0.1624713	1.883	0.000098	-673.94
1758.5	153.38	0.1700727	1.9711	0.000115	-673.59
1891.2	159.02	0.16404	1.9012	0.0001232	-674.1
2023.6	171.88	0.1517667	1.7589	0.0001307	-674.68
2191.7	161.4	0.1616281	1.8732	0.000141	-673.17
2456.8	168.59	0.1547282	1.7932	0.0001564	-673.86
2721.9	168.11	0.1551731	1.7984	0.0001719	-673.5
2854.5	176.99	0.1473882	1.7082	0.0001793	-674.21
2987.1	179.72	0.1451483	1.6822	0.0001865	-673.65
3119.6	171.33	0.1522532	1.7646	0.0001941	-673.05
3384.9	173.82	0.1500757	1.7393	0.0002092	-673.22
3650	180.37	0.1446251	1.6762	0.0002236	-673.1
3782.8	186.14	0.1401467	1.6243	0.0002306	-673.35
3915.3	193.48	0.1348282	1.5626	0.0002373	-673.43
4180.8	182.01	0.1433257	1.6611	0.0002517	-673.16
4445.9	185.16	0.1408875	1.6328	0.0002658	-672.72
4578.3	190.98	0.1365921	1.5831	0.0002726	-673.26
4711	187.03	0.1394795	1.6165	0.0002795	-672.94
Average			1.832811538		

Table B2: LPR result for 40ppm Inhibition Corrosion Rate

Time (Sec)	LPR (ohm.cm²)	Icorr (mA/cm²)	Corrosion Rate (mm/year)	Total metal loss (mm)	Potential (mV)
0	178.92	0.1458016	1.6898	0	-671.21
132.72	203.01	0.1284979	1.4892	6.43E-06	-673.02
300.03	186.95	0.139539	1.6172	1.52E-05	-672.36
432.82	204.13	0.1277903	1.481	2.16E-05	-673.51
697.8	188.4	0.1384591	1.6047	3.54E-05	-672.56
963.09	186.45	0.1399082	1.6215	4.94E-05	-672.56
1095.4	201.29	0.1295926	1.5019	5.59E-05	-673.46
1227.7	198.52	0.1314064	1.523	6.24E-05	-673.36
1395.6	197.28	0.1322323	1.5325	7.08E-05	-672.76
1660.5	185.19	0.1408648	1.6326	8.49E-05	-672.16
1926.7	186.8	0.1396514	1.6185	0.0000989	-672.4
2059.4	194.58	0.1340642	1.5538	0.0001056	-672.88
2191.8	199.93	0.1304772	1.5122	0.0001121	-673.03
2457.5	186.54	0.1398394	1.6207	0.0001261	-672.07
2722.3	184.33	0.1415191	1.6402	0.0001402	-672.06
2854.8	206.45	0.1263584	1.4644	0.0001465	-673.1
3119.9	183.51	0.1421494	1.6475	0.0001607	-671.88
3384.9	184.17	0.1416452	1.6416	0.0001749	-671.96
3517.2	201.71	0.1293285	1.4989	0.0001813	-672.74
3649.6	196.04	0.1330652	1.5422	0.0001879	-672.61
3817.7	195.92	0.1331487	1.5431	0.0001964	-672.14
4082.4	186.33	0.1400027	1.6226	0.0002103	-671.69
4347.4	187.32	0.1392611	1.614	0.0002243	-671.87
4479.8	201.27	0.1296096	1.5021	0.0002307	-672.78
4612.2	202.41	0.1288805	1.4937	0.0002371	-672.42
4877.2	190.58	0.1368812	1.5864	0.0002508	-671.66
Average			1.56905		

Table B3: LPR result for 80ppm CI Inhibited Corrosion Rate

Time (Sec)	LPR (ohm.cm²)	Icorr (mA/cm²)	Corrosion Rate (mm/year)	Total metal loss (mm)	Potential (mV)
0	249.71	0.1044686	1.2107	0	-694.72
264.83	241.83	0.1078688	1.2501	1.08E-05	-694.55
397.18	268.93	0.0969996	1.1242	1.56E-05	-695.55
529.7	254.91	0.1023374	1.186	2.07E-05	-694.64
697.23	244.3	0.106779	1.2375	2.75E-05	-694.31
962	226.87	0.114986	1.3326	3.89E-05	-693.88
1226.9	240.66	0.1083956	1.2563	4.98E-05	-693.75
1359.5	267.64	0.097469	1.1296	5.46E-05	-694.62
1491.9	250.4	0.1041801	1.2074	5.98E-05	-694.21
1624.4	260.21	0.1002508	1.1619	6.48E-05	-694.17
1889.7	231.36	0.1127506	1.3067	7.61E-05	-692.95
2155.3	234.29	0.1113434	1.2904	8.72E-05	-692.97
2287.6	251.86	0.1035737	1.2004	0.0000924	-693.24
2420.2	253.71	0.1028192	1.1916	0.0000975	-693.09
2690.7	229.94	0.1134463	1.3148	0.0001091	-691.87
2955.7	235.27	0.1108788	1.285	0.0001202	-692.09
3088.1	261.09	0.0999129	1.1579	0.0001252	-692.85
3220.5	254.05	0.1026813	1.19	0.0001303	-692.4
3388.5	232.75	0.1120786	1.2989	0.0001374	-691.07
3654.2	223.23	0.1168571	1.3543	0.0001491	-690.81
3919.5	225.76	0.1155488	1.3392	0.0001606	-690.94
4051.9	251.13	0.1038767	1.2039	0.0001658	-692.08
4184.6	244.1	0.1068659	1.2385	0.0001711	-691.29
4317.2	250.74	0.1040367	1.2057	0.0001763	-691.37
			1.2364		

Table B4: LPR result for 120ppm CI inhibited Corrosion Rate

Time (Sec)	LPR (ohm.cm²)	Icorr (mA/cm²)	Corrosion Rate (mm/year)	Total metal loss (mm)	Potential (mV)
0	496.14	0.052579	0.6093908	0	-683.66
265.62	244.25	0.1068014	1.2378	1.07E-05	-673.2
530.68	232.66	0.1121236	1.2995	2.19E-05	-672.75
663.41	254.82	0.1023706	1.1864	2.70E-05	-673.91
928.78	228.46	0.1141834	1.3233	3.84E-05	-673.21
1194	227.37	0.1147314	1.3297	4.99E-05	-673.68
1326.9	255.82	0.101972	1.1818	5.50E-05	-675.21
1459.3	252.6	0.1032725	1.1969	6.02E-05	-674.99
1724.3	224.79	0.1160472	1.3449	7.17E-05	-673.92
1989.7	227.23	0.1148033	1.3305	8.32E-05	-674.28
2122.2	254.35	0.1025608	1.1886	8.83E-05	-675.58
2254.9	241.27	0.1081222	1.2531	0.0000937	-674.95
2422.7	235.11	0.1109518	1.2859	0.0001008	-674.45
2687.6	224.23	0.116339	1.3483	0.0001124	-674.11
2952.8	226.71	0.1150648	1.3336	0.0001239	-674.19
3085.2	252.22	0.1034288	1.1987	0.000129	-675.29
3217.7	240.14	0.1086307	1.259	0.0001345	-674.83
3350.1	248.85	0.1048268	1.2149	0.0001397	-675.06
3615.2	216.07	0.1207324	1.3992	0.0001517	-673.68
			1.2379732		

Table B5: LPR result for 320ppm CI Inhibited Corrosion Rate

Time (Sec)	LPR (ohm.cm²)	Icorr (mA/cm²)	Corrosion Rate (mm/year)	Total metal loss (mm)	Potential (mV)
0	315.24	0.0827525	0.959102	0	-679.79
132.14	310.8	0.0839334	0.9727882	4.18E-06	-678.55
264.62	285.18	0.0914731	1.0601	8.75E-06	-677.36
397.1	280.34	0.0930533	1.0784	1.34E-05	-677.27
661.93	241.64	0.1079542	1.2511	2.42E-05	-676.3
927.41	245.71	0.1061687	1.2304	3.48E-05	-676.98
1059.8	275.06	0.0948394	1.0991	3.95E-05	-678.68
1192.3	263.91	0.0988462	1.1456	4.45E-05	-678.4
1360.2	252.23	0.1034242	1.1986	5.10E-05	-678.15
1624	242.14	0.1077348	1.2486	6.17E-05	-678.24
1887.9	239.84	0.1087659	1.2605	7.25E-05	-678.56
2019.8	261.29	0.0998381	1.1571	7.75E-05	-679.51
2152	256.47	0.1017131	1.1788	8.26E-05	-679.41
2283.8	264.72	0.0985428	1.1421	8.74E-05	-679.67
2548	236.44	0.1103306	1.2787	0.0000984	-678.52
2811.5	228.88	0.1139761	1.3209	0.0001097	-678.21
2943.3	266.42	0.0979166	1.1348	0.0001146	-680.07
3075.3	251.57	0.1036964	1.2018	0.0001198	-679.34
3339.2	227.01	0.1149151	1.3318	0.0001312	-678.21
3603.3	226.95	0.1149413	1.3321	0.0001426	-678.06
3735.4	261.82	0.0996339	1.1547	0.0001476	-679.94
3867.3	250	0.1043478	1.2093	0.0001528	-679.2
4035.7	231.03	0.1129156	1.3086	0.0001599	-678.24
4299.6	231.77	0.112552	1.3044	0.0001711	-678.15
			1.189974592		

Table B6: LPR result for 320ppm CI Inhibited Corrosion Rate Second Run

Time (Sec)	LPR (ohm.cm²)	Icorr (mA/cm²)	Corrosion Rate (mm/year)	Total metal loss (mm)	Potential (mV)
0	315.24	0.0827525	0.959102	0	-679.79
132.14	310.8	0.0839334	0.9727882	4.18E-06	-678.55
264.62	285.18	0.0914731	1.0601	8.75E-06	-677.36
397.1	280.34	0.0930533	1.0784	1.34E-05	-677.27
661.93	241.64	0.1079542	1.2511	2.42E-05	-676.3
927.41	245.71	0.1061687	1.2304	3.48E-05	-676.98
1059.8	275.06	0.0948394	1.0991	3.95E-05	-678.68
1192.3	263.91	0.0988462	1.1456	4.45E-05	-678.4
1360.2	252.23	0.1034242	1.1986	5.10E-05	-678.15
1624	242.14	0.1077348	1.2486	6.17E-05	-678.24
1887.9	239.84	0.1087659	1.2605	7.25E-05	-678.56
2019.8	261.29	0.0998381	1.1571	7.75E-05	-679.51
2152	256.47	0.1017131	1.1788	8.26E-05	-679.41
2283.8	264.72	0.0985428	1.1421	8.74E-05	-679.67
2548	236.44	0.1103306	1.2787	0.0000984	-678.52
2811.5	228.88	0.1139761	1.3209	0.0001097	-678.21
2943.3	266.42	0.0979166	1.1348	0.0001146	-680.07
3075.3	251.57	0.1036964	1.2018	0.0001198	-679.34
3339.2	227.01	0.1149151	1.3318	0.0001312	-678.21
3603.3	226.95	0.1149413	1.3321	0.0001426	-678.06
3735.4	261.82	0.0996339	1.1547	0.0001476	-679.94
3867.3	250	0.1043478	1.2093	0.0001528	-679.2
4035.7	231.03	0.1129156	1.3086	0.0001599	-678.24
4299.6	231.77	0.112552	1.3044	0.0001711	-678.15
4565.2	232.07	0.112406	1.3027	0.0001824	-678.1
4697.6	259.26	0.1006207	1.1661	0.0001874	-679.31
			1.193391931		

Table B7: LPR result for 1000ppm CI Inhibited Corrosion Rate

Time (Sec)	LPR (ohm.cm²)	Icorr (mA/cm²)	Corrosion Rate (mm/year)	Total metal loss (mm)	Potential (mV)
0			0		
0	250.38	0.1041862	1.2075	0	-680.35
263.58	256.33	0.1017687	1.1794	1.01E-05	-680.85
527.5	253.1	0.1030669	1.1945	2.04E-05	-680.08
791.73	251.46	0.1037398	1.2023	3.07E-05	-680.4
1055.6	246.05	0.1060198	1.2287	4.12E-05	-679.65
1187.4	249.53	0.1045437	1.2116	4.64E-05	-679.41
1319.2	265.82	0.0981371	1.1374	5.13E-05	-679.36
1582.8	266.21	0.0979922	1.1357	6.10E-05	-680.31
1846.5	274.47	0.0950438	1.1015	7.05E-05	-679.78
1978.2	252.97	0.1031192	1.1951	7.56E-05	-678.7
2110	255.07	0.1022702	1.1853	8.07E-05	-679.2
2241.9	263.08	0.0991565	1.1492	8.56E-05	-678.83
2505.8	261.95	0.0995871	1.1542	0.0000955	-680.18
2769.7	258.37	0.1009661	1.1701	0.0001055	-679.44
2901.3	259.82	0.1004004	1.1636	0.0001105	-678.6
3033.2	265.28	0.0983355	1.1397	0.0001154	-679.09
3201.5	273.12	0.0955144	1.107	0.0001215	-679.77
3465.2	265.17	0.0983753	1.1401	0.0001312	-679.02
3729.1	270.65	0.0963833	1.117	0.0001408	-678.95
3861	261.3	0.0998332	1.157	0.0001458	-678.15
3992.7	260.81	0.10002	1.1592	0.0001507	-678.37
4124.7	279.77	0.0932423	1.0806	0.0001554	-678.95
4388.6	256.32	0.1017723	1.1795	0.0001655	-678.53
4652.5	269.26	0.0968835	1.1228	0.0001751	-678.7
4784.5	263.21	0.0991094	1.1486	0.0001801	-677.86
4916.3	258.67	0.1008471	1.1688	0.0001851	-677.78
Average			1.15909231		

APPENDIX C

Linear Polarization Resistance Result (LPR)
Laboratory Testing 2:
Study on Low Corrosion Inhibitor Availability Effect on Corrosion Rate

Table C1: LPR result for 20ppm CI inhibited corrosion rate

Time (Sec)	LPR (ohm.cm²)	Icorr (mA/cm²)	Corrosion Rate (mm/year)	Total metal loss (mm)	Potential (mV)
0	131.57	0.1982655	2.2978	0	-649.14
132.42	177.05	0.14734	1.7076	7.35E-06	-652.53
300.39	154.72	0.1685983	1.954	1.80E-05	-651.53
564.4	146.45	0.1781274	2.0644	3.57E-05	-651.9
828.2	156.4	0.1667875	1.933	5.23E-05	-652.46
960.16	169.91	0.1535295	1.7794	6.00E-05	-653.31
1091.9	166.88	0.156313	1.8116	6.77E-05	-653.09
1223.8	170.35	0.1531331	1.7748	7.53E-05	-653.52
1487.6	152.56	0.1709843	1.9817	0.0000923	-653.19
1751.1	156.99	0.166164	1.9258	0.0001088	-653.57
1882.7	176.35	0.1479204	1.7143	0.0001162	-654.76
2014.3	172.88	0.1508953	1.7488	0.0001236	-654.28
2285.9	157.33	0.1658102	1.9217	0.0001406	-653.58
2549.6	157.17	0.1659738	1.9236	0.0001571	-653.45
2681.3	173.41	0.1504282	1.7434	0.0001646	-654.09
2813	162.23	0.1607997	1.8636	0.0001725	-654.2
2981.7	171.87	0.1517804	1.7591	0.0001822	-654.45
3245.6	160.6	0.162431	1.8825	0.0001983	-654.01
3509.5	159.96	0.1630827	1.8901	0.0002146	-654.26
3641.3	181.28	0.1439026	1.6678	0.0002217	-655.29
3773.1	173.54	0.1503192	1.7421	0.0002292	-654.93
3904.9	179.32	0.1454714	1.686	0.0002364	-655.26
4168.8	161.75	0.1612793	1.8692	0.0002524	-654.49
4432.6	161.76	0.1612689	1.8691	0.0002685	-654.63
4564.5	185.88	0.1403386	1.6265	0.0002754	-656.11
4696.5	174.74	0.1492833	1.7301	0.0002829	-655.58
			1.822808		

Table C2: LPR result for 30ppm CI inhibited corrosion rate

Time (Sec)	LPR (ohm.cm²)	Icorr (mA/cm²)	Corrosion Rate (mm/year)	Total metal loss (mm)	Potential (mV)
0	175.19	0.1489023	1.7257	0.00E+00	-657.12
131.93	186.92	0.1395575	1.6174	6.94E-06	-658.12
300.05	190.77	0.1367442	1.5848	1.56E-05	-657.97
563.97	181.14	0.1440134	1.6691	2.99E-05	-657.3
827.65	180.09	0.1448494	1.6788	4.43E-05	-657.45
959.61	194.9	0.1338438	1.5512	5.10E-05	-657.93
1091.6	184.63	0.1412894	1.6375	5.80E-05	-657.41
1223.3	190.38	0.1370249	1.5881	6.48E-05	-658.24
1486.9	187.3	0.1392779	1.6142	7.86E-05	-657.61
1750.5	184.1	0.1416932	1.6422	0.0000927	-657.47
1882.3	201.66	0.1293604	1.4992	0.0000991	-658.05
2014.2	193.79	0.1346138	1.5601	0.0001058	-657.69
2182.6	187.01	0.1394876	1.6166	0.0001147	-657.08
2314.4	195.36	0.1335292	1.5476	0.0001213	-657.49
2483.1	187.88	0.1388453	1.6092	0.0001301	-656.77
2615.2	196.21	0.1329518	1.5409	0.0001367	-657.3
2783.2	193.34	0.1349224	1.5637	0.0001453	-657.06
2915	193.54	0.1347882	1.5621	0.000152	-657.07
3083.3	186.59	0.1398085	1.6203	0.0001609	-656.77
3215.5	198.55	0.1313808	1.5227	0.0001674	-657.58
3383.3	193.55	0.1347801	1.5621	0.0001759	-656.98
3515.8	193.96	0.134494	1.5587	0.0001826	-657.3
3683.5	190.32	0.1370678	1.5886	0.0001913	-656.89
3816.3	201.55	0.1294316	1.5001	0.0001978	-657.49
3983.9	194.1	0.1343992	1.5576	0.0002063	-657.1
4116.3	202.01	0.1291363	1.4966	0.0002127	-657.73
			1.585196154		

Table C3: LPR result for 50ppm CI inhibited corrosion rate

Time (Sec)	LPR (ohm.cm²)	Icorr (mA/cm²)	Corrosion Rate (mm/year)	Total metal loss (mm)	Potential (mV)
0	181.15	0.1440061	1.669	0	-655.85
132.36	204.2	0.1277473	1.4805	6.37E-06	-657.64
300.47	184.74	0.1412084	1.6366	1.53E-05	-656.65
432.88	199.07	0.13104	1.5187	2.19E-05	-657.85
600.77	187.82	0.1388894	1.6097	3.06E-05	-657.17
865.94	183.06	0.1424979	1.6515	4.49E-05	-657
1131.2	180.91	0.1441955	1.6712	5.93E-05	-656.78
1263.6	204.62	0.1274848	1.4775	6.57E-05	-658.44
1395.9	193.92	0.1345217	1.5591	7.24E-05	-657.61
1528.5	194.73	0.1339617	1.5526	7.91E-05	-657.86
1793.6	188.34	0.1385098	1.6053	0.0000929	-657.12
2058.6	182.94	0.1425912	1.6526	0.0001071	-657.34
2191.1	209.58	0.1244711	1.4426	0.0001133	-658.23
2323.5	195.58	0.1333781	1.5458	0.00012	-657.7
2588.4	183.58	0.1420966	1.6469	0.0001342	-657.24
2853.6	187.18	0.1393675	1.6152	0.0001481	-657.45
2985.9	198.01	0.1317446	1.5269	0.0001547	-658.02
3118.2	190.35	0.1370413	1.5883	0.0001615	-657.99
3286.4	190.06	0.1372557	1.5907	0.0001702	-657.34
3551.6	187.32	0.1392608	1.614	0.0001841	-657.43
3816.6	183.61	0.1420738	1.6466	0.0001983	-657.24
3949.2	197.06	0.1323756	1.5342	0.0002049	-658.01
4081.5	192.32	0.1356381	1.572	0.0002117	-657.62
4214	194.63	0.1340329	1.5534	0.0002184	-657.75
4478.9	185.49	0.1406336	1.6299	0.0002324	-657.12
4744.1	183.15	0.1424274	1.6507	0.0002466	-656.85
			1.586211538		

APPENDIX D

Linear Polarization Resistance Result (LPR)

Laboratory Testing 3:

Determination of Corrosion Inhibitor Efficiency at the Optimum Dosage

Table D1: LPR result of 80ppm Inhibited Corrosion Rate

Time (Sec)	LPR (ohm.cm²)	Icorr (mA/cm²)	Corrosion Rate (mm/year)	Total metal loss (mm)	Potential (mV)
0	216.6036	0.120034961	1.405	0	-680.35
264.62	220.5595	0.117882021	1.3798	1.16E-05	-680.85
529.45	205.7104	0.126391261	1.4794	3.64E-05	-680.08
661.65	228.5259	0.113772639	1.3317	6.44E-05	-680.4
794.22	203.3327	0.127869271	1.4967	1.02E-04	-679.65
926.88	222.804	0.116694486	1.3659	1.42E-04	-679.41
1192.3	230.569	0.112764516	1.3199	1.92E-04	-679.36
1457.1	222.1534	0.117036223	1.3699	2.55E-04	-680.31
1589.5	222.1859	0.117019136	1.3697	3.24E-04	-679.78
1721.8	230.1679	0.112961015	1.3222	3.97E-04	-678.7
1898.3	215.1945	0.120820955	1.4142	4.82E-04	-679.2
2164	207.5766	0.125254987	1.4661	5.82E-04	-678.83
2428.6	243.1123	0.106946451	1.2518	6.79E-04	-680.18
2560.8	234.966	0.110654293	1.2952	7.84E-04	-679.44
2693.5	229.2662	0.113405272	1.3274	8.97E-04	-678.6
2959	227.1274	0.114473199	1.3399	1.02E-03	-679.09
3224.9	228.1148	0.113977681	1.3341	1.16E-03	-679.77
3357.3	224.1167	0.116011013	1.3579	1.30E-03	-679.02
3489.9	219.2723	0.118574037	1.3879	1.46E-03	-678.95
3622.7	225.6789	0.115207932	1.3485	1.61E-03	-678.15
3887.9	228.0977	0.113986224	1.3342	1.78E-03	-678.37
4152.7	220.3519	0.117993085	1.3811	1.96E-03	-678.95
4285	228.8697	0.113601771	1.3297	2.14E-03	-678.53
4417.4	224.53	0.115797428	1.3554	2.33E-03	-678.7
4585.3	225.2946	0.115404431	1.3508	2.53E-03	-677.86
4850.5	222.332	0.116942245	1.3688	2.74E-03	-677.78
	Average		1.364738462		