Reliability-Based Maintenance System for Offshore Pipelines in Malaysia

by

Syafiqa Binti Abdul Manan

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Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved by,

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(Dr. Zahiraniza Binti Mustaffa)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

May 2013

CERTIFICATION OF ORIGINALITY

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

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SYAFIQA BINTI ABDUL MANAN

ABSTRACT

Pipelines, like other structures in nature, deteriorate over time. The deterioration of pipeline in the form of corrosion is found to be a major problem to the pipeline operators and it becomes even worse as a pipeline ages. Pipeline operators throughout the world are faced with the expensive and risky task of operating aged pipeline because of corrosion and its destructive effect. Hence, a proper maintenance program which involves the injection of corrosion inhibitor for these pipelines is crucial to maintain a safe and continuous operation. Due to the fact that there are no codes providing the rule of thumb of releasing corrosion inhibitor into the pipeline system, most of the operators are confronted with the problem in optimizing the maintenance schedule. A study on the probabilistic methodology for the purpose of creating a reliability based maintenance system that optimizes the corrosion inhibitor injection for offshore pipelines in Malaysian waters is presented in this research.

ACKNOWLEDGEMENT

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF RESEARCH

1.1.1 Corrosion in Pipelines

Pipelines are the main 'arteries' of the oil and gas business as they are used as means of transporting gases and liquids over long distances from their sources to the ultimate customers. They have been used for thousands of years and believed to be the most economical transportation in oil and gas industry. With their impressive safety records as majority of them are below ground, pipelines can practically guarantee uninterrupted service. It was recorded that the first use of a pipe to transport a hydrocarbon was in China, where bamboo pipe was used by the Chinese to transmit natural gas to light their capital, Peking about 2,500 years ago (Hopkins, 2007).

All engineering structures deteriorate over time and pipelines are no exclusion. Corrosion has long been acknowledged as the most dominant cause of high pressure gas and oil pipeline rupture. According to the BS7361: *Cathodic Protection, Code of Practice for Land and Marine Applications*, corrosion is defined as the chemical or electrochemical reaction of a metal with its environment that can lead to progressive deterioration. For pipeline corrosion, it can occur at two locations which are either internal or external pipe wall or even both. In regards to internal corrosion, the environment would be water containing other contaminants such as oxygen, (O_2), hydrogen sulphide, (H_2S), carbon dioxide (CO_2), chlorides and microorganisms while for external corrosion of offshore pipelines, the environment would be seawater.

The main effect of corrosion is the loss of metal cross-section of the pipeline which results in reduction of its integrity and also safety. Without a practical and effectual corrosion-prevention strategy, corrosion will continue to develop and the cost of repairing deteriorating pipeline will escalate (Md. Noor *et al*., 2011). For instance, it was reported that due to BP's Mexico Gulf Oil pipeline spilling, a rate of 0.6 – 1.2 million gallons of oil was leaking from the bottom of the sea per day. The estimation of total financial loss was about 23 billion USD and the most critical part is huge environmental disasters have been showing up (Belachew, 2011). According to the society of corrosion, *NACE International*, the total annual cost of corrosion in the oil and gas production industry is estimated to be $1.372, broken down into some elements in which one of the elements includes, $320 million in capital expenditures related to corrosion. With an effective corrosion management, those benefits could be achieved:

- Statutory or corporate compliance with safety, health and environment policies
- Reduction in leaks
- Reduction in deferment costs
- Increased plant availability

1.1.2 Corrosion Inhibitor

Oil and gas pipelines are vulnerable to corrosion. The intensity of corrosion is determined by the chemical composition of the products carried in the pipeline out of which the main responsible components are H_2S, CO_2, water and chloride contents. One of the common ways to control corrosion in a pipeline is by releasing a corrosion inhibitor. As an alternative to the use of high alloy components for the pipeline materials, which are expensive in relation to common carbon steels, corrosion inhibitors have been the best choice in mitigating the occurrence of corrosion in the pipeline system. Corrosion inhibitor is defined as a chemical compound that capable to decrease the corrosion rate of a material when it was added to a liquid or gas and the material is normally a metal or an alloy (Mustaffa, 2011).

The mechanism of corrosion inhibitor is attributed to the absorption of the inhibitor on the pipe wall to form hydrophobic layer, thus does not allow water from contacting the pipe wall (Chen *et al.*, 2003). Historically, concept of corrosion inhibitor efficiency has been used to describe corrosion inhibitor performance 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 (Ho, 2008). Corrosion inhibitor efficiency is based on the formula given below:

$$\text{Inhibitor Efficiency (\%)} = 100 \times (CR_{uninhibited} - CR_{inhibited}) / CR_{uninhibited} \quad (1.1)$$

Where,

$CR_{uninhibited}$ = uninhibited corrosion rate (mm/yr)

$CR_{inhibited}$ = inhibited corrosion rate (mm/yr)

Generally, the inhibitor efficiency increases with an increase in inhibitor concentration. The problem with this approach is that, long term field monitoring often indicates lower efficiency compared to the efficiency achieved in laboratory testing because in the field, there will be periods when the injection activity could not be carried out due to operation problem such as, pump failure, etc. (Marsh *et al.*, 2007). Because of this issue, the concept of corrosion inhibitor availability is developed.

Using the concept of inhibitor availability, the field performance is determined based on the summation of total metal loss over field life. Formula shown below is used to calculate the corrosion inhibitor availability in the pipeline and it is calculated according to the life time period of the pipeline (Ho, 2008). The availability concept is simply the percentage of time that the inhibitor is actually 'available' in the system at the required dosage.

Availability (%) = 100 x time inhibitor is actually added at or above the minimum dosage / lifetime (1.2)

1.2 PROBLEM STATEMENT

Corrosion is one of the major problems in the oil and gas sector during the extraction, transportation and storage of the products. Inhibited corrosion rate on all parts of the pipeline is not something that can be measured on a daily basis since the corrosion monitoring is only limited to certain locations. Therefore, inhibitor residuals concept is applied in order to check if the pipeline is protected or not. If the inhibitor residual concentration in the water phase exiting the pipeline is above a certain target level, then the whole pipeline is assumed to be protected by the inhibitor (Rippon, 2003).

It is essential to keep the inhibitor concentration as close as to and above the minimum required at all time in order to effectively control corrosion in the pipeline in the most cost effective way. As mentioned above, the inhibitor concentration is the key for day to day assessment of the inhibitor system availability. Leaving a pipeline without inhibition within a period of time might cause the corrosion to grow rapidly.

1.3 OBJECTIVES AND SCOPE OF RESEARCH

The main objectives of this research are:

1. To propose a reliability model for corroded offshore pipelines in Malaysian water based on historical operation of the release of corrosion inhibitors in the pipe.
2. To propose maintenance system that optimizes the corrosion inhibitor injection practice for corroded pipelines in Malaysian water.

The scope of study of this research is to assess the importance for corrosion inhibitor to present at all the time during pipeline operation based on the analysis of historical operation of the selected pipeline.

1.4 THE RELEVANCY OF RESEARCH

With reference to the scope of research highlighted in the previous section, one of the corroded pipelines in Malaysian waters will be assessed by using a reliability-based maintenance model developed based on the general limit state function with details can be referred to Section 2.4 later. This research outcome would be used to educate the pipeline operators in optimizing the inhibitor injection practice for the safe operation of their pipelines.

1.5 FEASIBILITY OF RESEARCH

The proposed reliability-based maintenance model is a general idea to see on how reliable the present operation of one of corroded pipelines in Malaysian waters. From the carried out analysis on 2009 data, this pipeline seemed not to be under the protection of corrosion inhibitor due to the non-detection of inhibitor in the pipeline system almost throughout the year and the other pipelines were also expected to be the same. Hence, this model will be used to assess this corroded pipeline and proper optimization techniques related to corrosion inhibitor released will be proposed to ensure a safe and continuous operation of it. This research will cover on probabilistic approaches which involve simulations using two different software and take approximately nine months upon completion.

CHAPTER 2

LITERATURE REVIEW

2.1 MECHANISM OF CORROSION IN PIPELINE

Large diameter, long distance multiphase flow lines are now the major trend in oil and gas production. Economics demand to use carbon steel as the material of construction (Kang *et al.,* 1999). However, carbon steel is prone to corrosion from the flowing mixture of the products. In addition, transportation of hydrocarbons is mainly by underground or undersea pipelines. As a result, it increases pipelines' risk to corrosive environment (Belachew, 2011). The U.S Department of Transportation's Research and Special Programs Administration, Office of Pipeline Safety had made compilation of data on pipeline accidents and their causes for pipeline failures in the USA for year of 2002 to 2003. The result in Table 2.1 shows that corrosion gives the highest threat for both oil and gas lines.

Table 2.1 Reported failure causes as compiled by the U.S Department of Transportation's Research and Special Programs Administration (2002-2003)

	Percentage of failures attributed to each category of cause in:	
Reported cause	**Oil lines**	**Gas lines**
Excavation	14.7	17.8
Natural Forces	4.8	6.7
Other Outside Force	4.4	8.9
Material Failure	16.5	20
Equipment Failure	15.4	6.7
Corrosion	**25.4**	**25.6**
Operations	5.2	3.3
Other	13.6	11
Total	100	100

Corrosion as defined by National Association of Corrosion Engineers International (NACE), the primary support organization in the corrosion industry, is the deterioration of a material, usually a metal which results from a reaction with its environment (Fessler, 2008). The corrosion process is usually electrochemical in nature. With respect to pipeline corrosion, the metal is the steel of the pipeline, mainly comprised of iron.

Corrosion involve two simultaneous chemical processes; oxidation and reduction processes. Oxidation is the process when electrons strip from an atom while reduction is the process of gaining electrons. The oxidation process takes place at anode region in which positively charged atoms leave the metal surface and enter into an electrolyte as ions. The ions leave their corresponding negative charge in the form of electrons in the metal which then move to the location of the cathode through a conductive path. At the cathode, reduction process takes place and consumes the free electrons. It can be seen that the essential mechanisms needed for a corrosion reaction to proceed are a cathode, an anode, an electrolyte and a direct electrical connection between the anode and the cathode. A simplified model for corrosion that occurs in pipeline is shown in Figure 2.1 below.

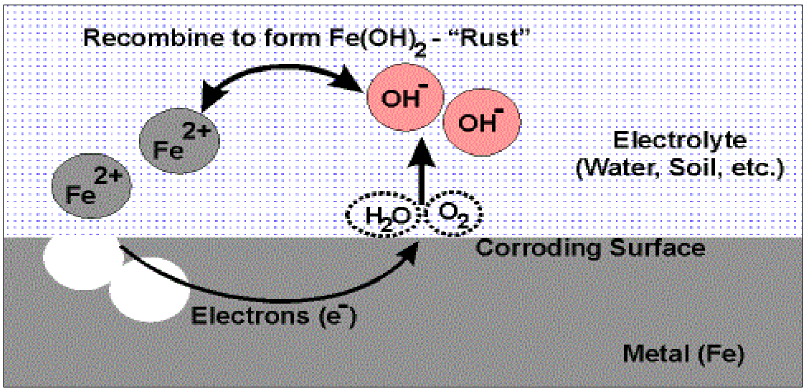


Figure 2.1 Simplified model of corrosion in pipeline

(Source: http://www.corrosion-club.com/basictheory.htm)

The biggest contributors to the internal corrosion on carbon steel pipelines carrying hydrocarbon products are the acid gases being either carbon dioxide (CO_2) for "sweet corrosion" or hydrogen sulphide (H_2S) for "sour corrosion".

Overall reaction of "sweet corrosion" is represented by the equation below,

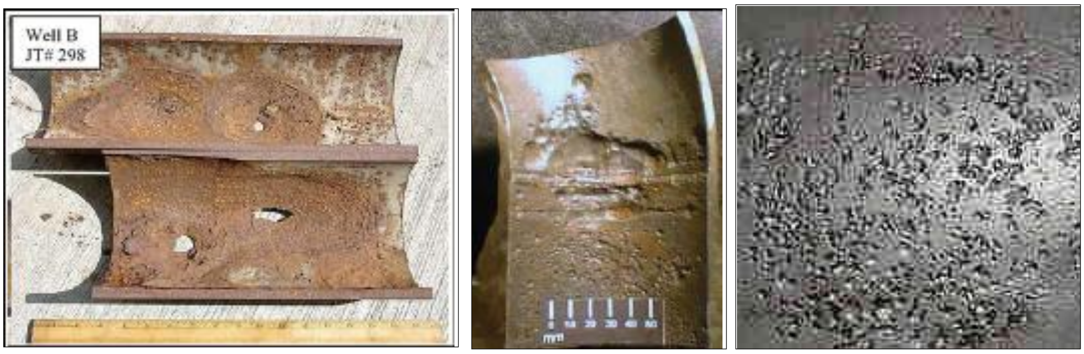
$$Fe + CO_2 + H_2O \longrightarrow FeCO_3 + H_2 \quad (2.1)$$

For "sour corrosion", the overall reaction is described by,

$$Fe + H_2S \longrightarrow FeS + H_2 \quad (2.2)$$

2.2 FORMS OF CORROSION

Metal loss due to corrosion can be observed either at the internal or external of the pipeline wall. Figure 2.2 shows samples of internal corrosions located in the pipelines. The behavior of the external corrosions is in the same way but at the opposite side of the pipeline wall (Mustaffa, 2011).



(a) (b) (c)

Figure 2.2 (a)(b) Examples of pipeline failure due to internal corrosions (Adapted from Mustaffa, 2011) (c) Pitting corrosion

The inspection of corroded pipelines was conducted by following Pipeline Operators Forum (POF) guidelines which classified pipeline defects into seven categories as Table 2.2 and the classification was defined with respect to thickness, width and length of the pipeline defects.

Table 2.2 Classification of pipeline defects according to Pipeline Operators Forum (POF) (Adapted from Balachew, 2011)

Type of Defects	**Definition**
Axial Grooving	$t \leq W < 3t$ and $L/W \geq 2$
Axial Slotting	$0 < L < t$ and $L \geq t$
Circumferential Grooving	$L/W \leq 0.5$ and $t \leq L < 3t$
Circumferential Slotting	$W \geq t$ and $0 < L < t$
Pitting	$(t \leq W < 6t$ and $t \leq L < 6t$ and $0.5 < L/W < 2)$ and not $(W \geq 3t$ and $L \geq 3t)$
Pinhole	$0 < W < t$ and $0 < L < t$
General	W ≥ 3t and L ≥ 3t

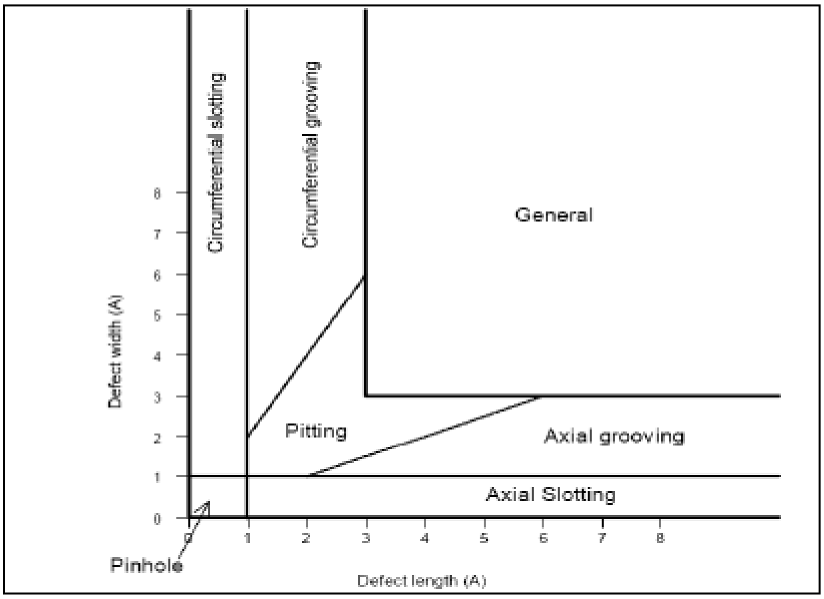
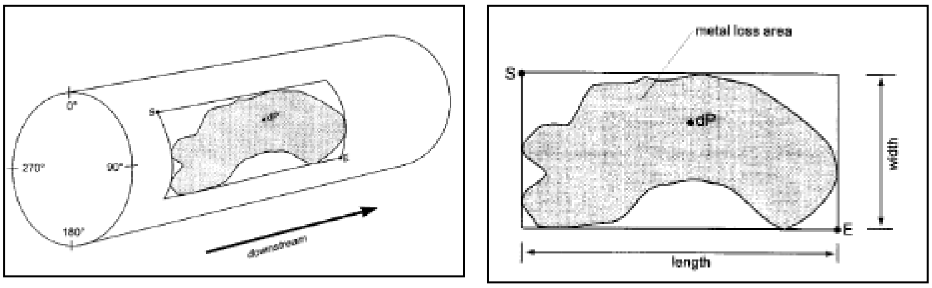


Figure 2.3 : Graphical presentations of metal loss anomalies per dimension class based on Pipeline Operators Forum (POF) (Adapted from Simek, 2009)

For better visual views of the corrosion shape, Figure 2.4 and Figure 2.5 are provided.



(a) (b)

Figure 2.4 : (a) Orientation of corrosion defect (b) Actual defect and overall defect dimension

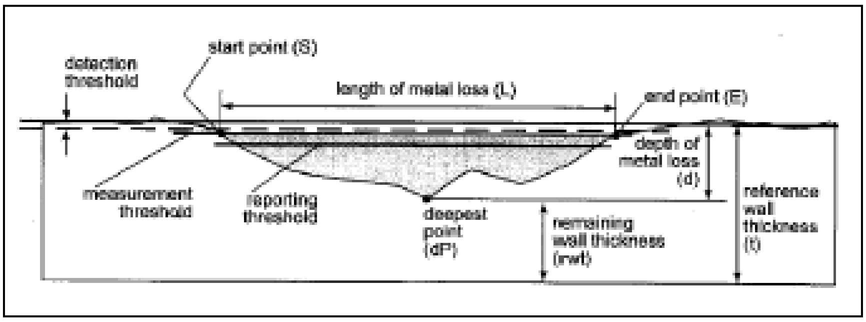


Figure 2.5 : Corrosion profile in pipeline

2.3 CORROSION INHIBITOR

The production facilities and pipeline infrastructure are essential to be properly monitored to ensure theirs system integrity as they are the assets to generate revenue for the owners. Corrosions, however, will always be the main threats to system integrity thus corrosion control must be seriously taken into consideration by the pipeline operators. In the processing industries and oil extraction, inhibitors have always been considered to be the first line of defense against corrosion. Releasing corrosion inhibitor into the pipeline is believed to be the most cost-effective method for providing corrosion protection in a system (Mustaffa, 2011). The corrosion inhibitors control the corrosion process by either decreasing the rate of anodic oxidation, cathodic reduction or both (Al Juhaiman *et al.,* 2013).

The main purpose of applying the corrosion inhibitor is to reduce the corrosion rate into an acceptable level. It has been assumed that the corrosion inhibitor will be injected into the system of pipeline at the correct dosage, without interruption during the lifetime of the system (Hedges *et al.*, 2000). But experience has shown that these assumptions are not applicable for a variety of reasons for example pumps failure, interruption on inhibitor supplies, and the worst case scenario is that, when it involves human intervention; inhibitor was not injected accordingly to its dosage and schedule which might cause corrosion to happen rapidly in the pipelines.

Corrosion injection system is critically dependant on the people element, particularly during operation (PETRONAS Technical Standard, 2010). Mustaffa (2011), in her present work on one of the pipelines in Malaysian waters has revealed that the corrosion inhibitor injection of this pipeline was not consistent throughout year 2009. Figure 2.6 below is the graph showing the corrosion inhibitor practice in the month of April.

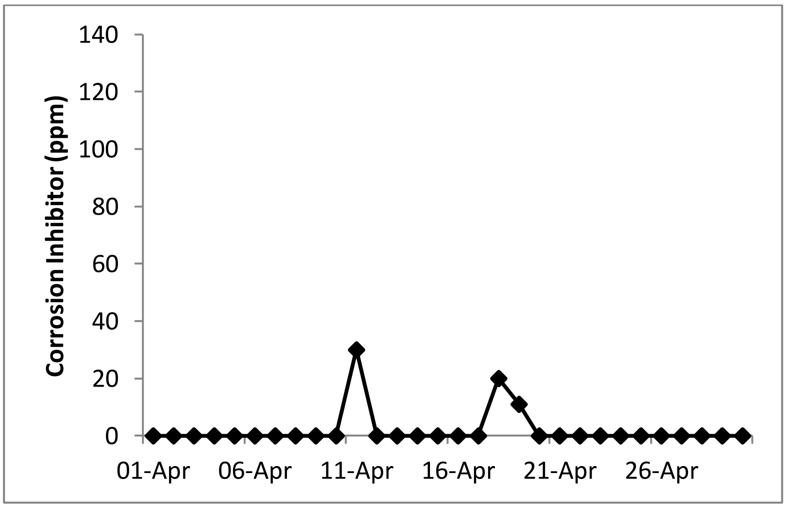


Figure 2.6 : Corrosion inhibitor practice carried out in April, 2009 by a pipeline operating in Peninsular Malaysia (Adapted from Mustaffa, 2011)

The data on the present analysis shows inconsistency of releasing the inhibitor as can be seen there were only 3 days in the month of April, the system was injected and the rest of 27 days marked with 0 ppm indicates the absence or non-detection of inhibitor in the pipeline system. The frequency of corrosion inhibitor injection for this pipeline obviously did not seem to follow any specific daily trends (Mustaffa, 2011). Another data dated in 2012 has been collected for the same pipeline. This data as shown in Figure 2.7, shows an improvement on the injection practice as there was consistency in the injection practice in term of days of injection, but still not meet the target as required by the recommended dosage. This is due to the fact that until today, there is no code that really explains the rule of thumb on how this injection of corrosion inhibitor practice should be carried out and practiced by the operators (Vosooghi, 2013).

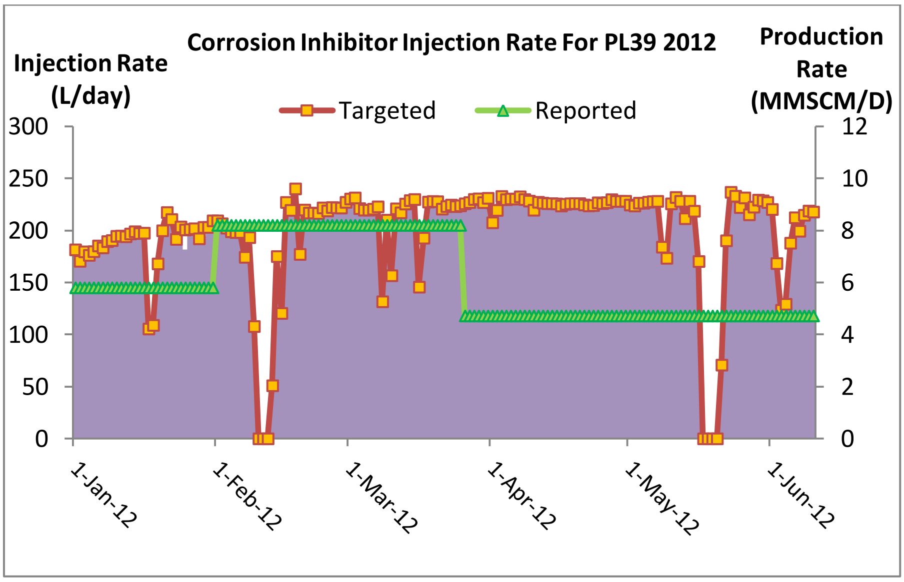


Figure 2.7 : Corrosion inhibitor practice carried out in 2012 by a pipeline operating in Peninsular Malaysia

Corrosion inhibitor dosage does affect the integrity of a pipeline (Ho, 2008). It has been proven by the experimental work shown in Figure 2.8 where the dosage of corrosion inhibitor required by one of pipeline in Prudhoe Bay was increasing from year 1990 to year 1999.

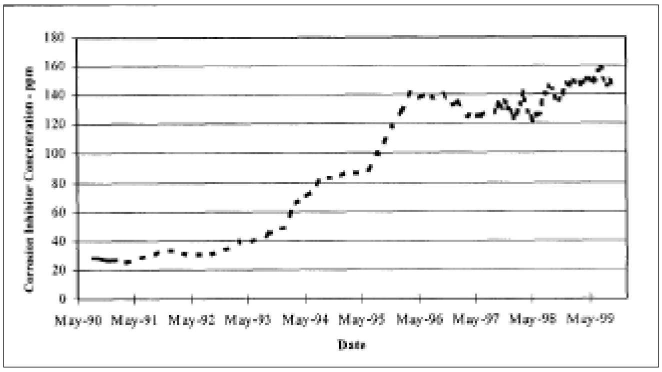


Figure 2.8 : Prudhoe Bay corrosion inhibitor dosage from 1990 - 1999 (Adapted from Hedges et al., 2000)

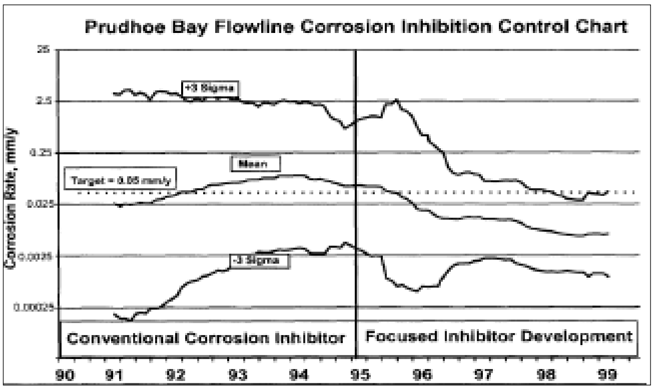


Figure 2.9 : The improvement in corrosion rate at Prudhoe Bay (Adapted from Hedges et al., 2000)

This pipeline was initially injected with inhibitor dosage of 25 ppm at year 1990. The dosage has been increased yearly until 1999 and the corrosion rate trend was monitored. From Figure 2.9, it can be seen that the corrosion rate was decreasing with the increasing of inhibitor dosage.

Experimental work by Hong *et al.* (2000) showed that inhibitor performance is correlated to the exposure time and concentration. When the inhibitor stays longer in the pipeline, it will form a more compact film around the pipe wall, thus provides a better protection against corrosion. He proposed the inhibitor to be present in the pipeline on daily basis as the inhibitor becomes less porous with the increase of exposure time and concentration.

2.4 LIMIT STATE, STRENGTH AND LOAD

For reliability analysis, a failure function which also known as a limit state function needs to be defined. This function expresses the criterion for failure of the pipeline (Ahammed, 1998). The limit state normally addresses as limit state function, *Z*.

$$Z = R - S \tag{2.3}$$

Where *R* is the strength or more generally the resistance to failure and *S* is the load or that which is conducive to failure (Mustaffa, 2011). The limit state is described by $Z = 0$. When the value of *Z* falls below 0, it indicates failure and when the value of *Z* is higher than 0, the pipeline is said to be under survival region. From this limit state function, the probability of failure can be obtained.

$$P_f = \mathrm{P_r}\,(Z \leq 0) = \mathrm{P_r}\,(R \geq S) \tag{2.4}$$

The reliability is the probability $\mathrm{P_r}\,(Z \geq 0)$, and is therefore when described in term of probability of failure becomes,

$$\mathrm{P_r}\,(Z > 0) = 1 - P_f \tag{2.5}$$

For this research, several limit state functions were developed in order to achieve the objectives targeted with details can be referred to Section 3.1.2. Interested readers are recommended to refer to other books on *Reliability Analysis* for future understanding on subjects beyond the scope of this research.

2.5 RANDOM VARIABLE AND PROBABILITY DISTRIBUTION

A random variable is any function that associates a numerical value to each possible outcome of an experiment. The value of the random variable will vary from trial to trial as the experiment is repeated (McColl *et al.*, 1997). There are two types of random variable which are discrete and continuous random variables. And these variables are associated with probability distribution which is typically defined in terms of the probability density function (PDF).

A probability density function of continuous random variables is a function which can be integrated to obtain the probability that the random variable takes a value in a given interval (McColl *et al.,* 1997). Some typical probability density functions used are uniform distribution, normal distribution, gamma distribution, lognormal distribution and many more. Each probability density function is normally described by mean (μ) and standard deviation (σ) values. The mean value is a measure of average while the standard deviation describes the dispersion of a random variable.

2.5.1 Normal Distribution

The normal distribution is an extremely important probability distribution in many fields. The standard normal distribution is the normal distribution with a mean of zero and a standard deviation of one and has a bell curve shaped.

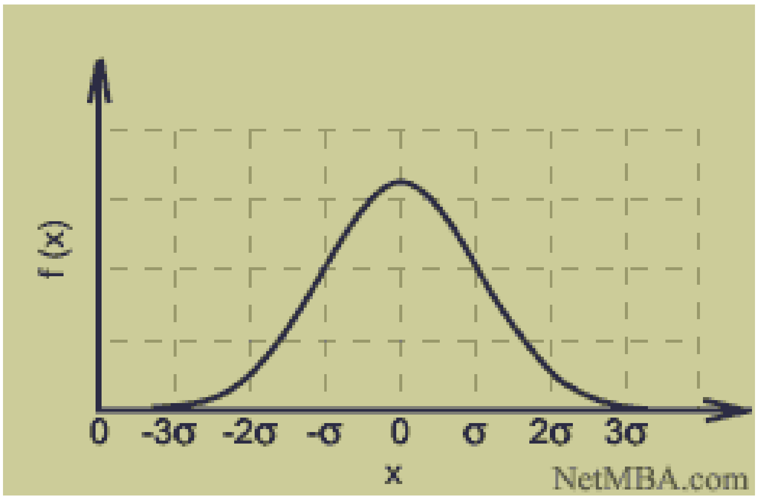


Figure 2.10 Bell-shaped of normal distribution (Adapted from http://www.netmba.com/statistics/distribution/normal/)

Generally, the normal distribution curve is described by the following probability density function :

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}}\, e^{\frac{-1}{2}(\frac{x-\mu}{\sigma})^2} \qquad (2.6)$$

For this type of distribution, the bell is having the symmetrical curve and extends to the positive and negative infinity. The value of area under the curve is equals to 1. It is a widely observed distribution as it can be applied to situations in which the data is distributed very differently.

The best probability density function that suits the raw data will be used for simulation that details can be referred in Chapter 3.

2.5.2 Monte Carlo Technique

In life, we are constantly faced with uncertainty and variability. Even though we have unprecedented access to complete information, we cannot accurately predict the future. From Monte Carlo simulation, all the possible outcomes could be seen and it allows us to assess the impact of risk from the decision we made which can help in making a better decision under any uncertainty.

Monte Carlo simulation relies on repeated random sampling to obtain numerical results. It performs risk analysis by running simulations over and over, each time using a different set of random values from the probability functions and often used when deterministic algorithm is not very feasible. Monte Carlo simulation could involve thousands of recalculations before it reaches the final results depending on the number of uncertainties. From this simulation, all the possible outcome values could be obtained. This technique often used in reliability engineering to generate mean time between failures and time to repair for components.

CHAPTER 3

METHODOLOGY

3.1 RESEARCH METHODOLOGY

This chapter presents the methodology adopted for this research. The methodology is simplified by the following process flowchart.

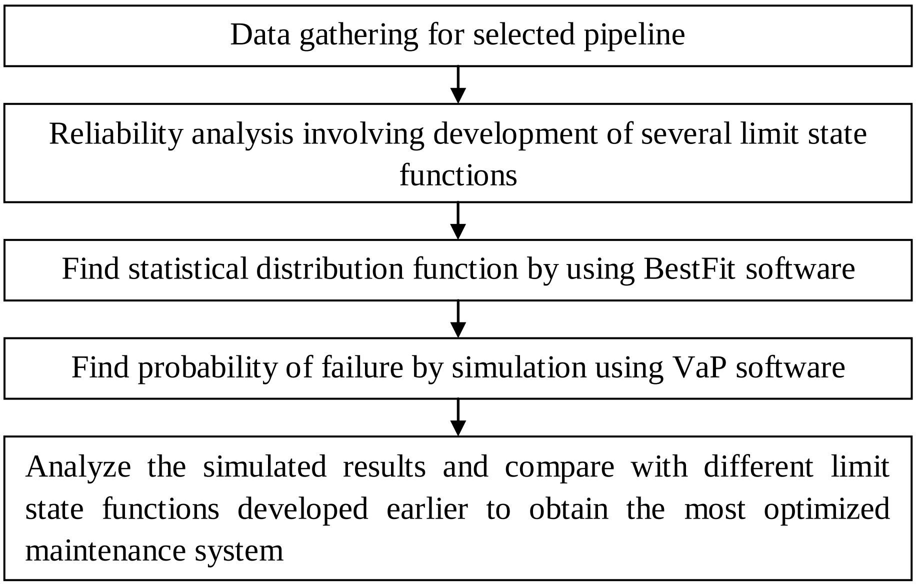


Figure 3.1 : Research methodology

3.1.1 Data Gathering

This research was begun with data gathering of the selected corroded pipeline. A 28" with length of 128.9 km pipeline transporting gas is chosen as the subject for this research. This pipeline located at offshore Terengganu, the east coast of Peninsular Malaysia and has been in operation for 14 years (1999 – 2013).

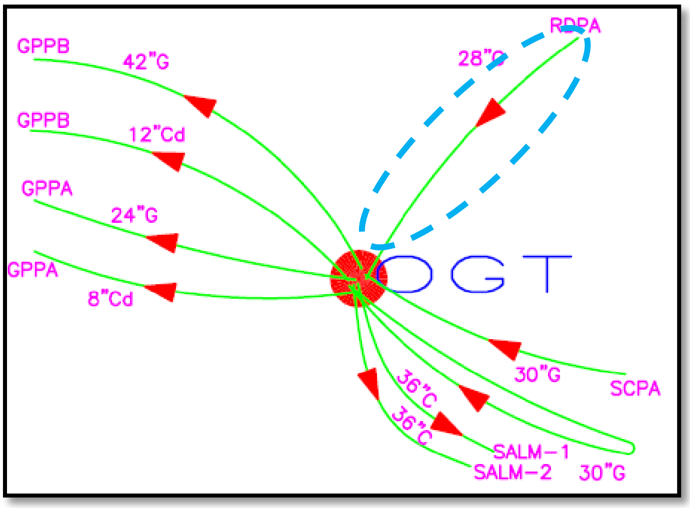


Figure 3.2 Layout of 28" gas pipeline in offshore Terengganu map

3.1.2 Development of Limit State Function

After completion of data gathering, the next step would be reliability analysis which involves the development of several limit state functions based on historical operation of releasing corrosion inhibitor into the pipelines system.

The first limit state function developed is as shown below:

$$g(x) = Z = d - (CR \text{ x } t_{absence}) \quad (3.1)$$

where,

d = Allowable corrosion depth

CR = Corrosion rate

$t_{absence}$ = Time when the corrosion inhibitor is absent in the pipeline

From equation (2.6), the strength, R of the pipeline system is described by the allowable corrosion depth, d. In a corroded pipeline, the corrosion will take up some of the pipe wall thickness. The remaining wall thickness which is not yet corroded is defined as d. Load, S is defined by the combination of estimated corrosion rate and the time when the pipeline is free from inhibition. In this model, the variable of $t_{absence}$ will be exploited. Corrosion in pipeline is unacceptable when the corrosion depth exceeds the allowable corrosion depth, d. The development of this reliability model thus indicates the achievement of Objective 1 of this research.

Second case is developed to study the influence of corrosion inhibitor towards the reliability of a pipeline. The limit state function for this case is as below:

$$g(x) = Z = d - (CR \times CI_{injected}/CI_{targeted} \times t_{absence}) \quad (3.2)$$

where,

$CI_{injected}$ = Amount of CI being injected into the pipeline

$CI_{targeted}$ = Amount of CI that is recommended to be injected

In this case, the variable of corrosion inhibitor is added in which the value of $CI_{injected}$ and $CI_{targeted}$ are obtained from the data collected based on the operation in year 2012. The result for this case will then be compared with the first case to see how the presence of corrosion inhibitor does affect the pipeline integrity by comparing their values of probability of failure.

For the third case, the same equation as the second case will be used but the value of $CI_{injected}$ will be exploited in three different models. This case was developed in order to see on how different corrosion inhibitor injection practices will affect the reliability of the pipeline system and from this case, the most optimized injection practice could be established.

Monte Carlo technique is used for simulation to determine the probability of failure of the system.

3.1.3 Statistical Distribution Function using BestFit

All variables in the limit state functions defined in Section 3.1.2 will be used as the main inputs to start the simulation in BestFit software. BestFit is distribution-fitting software that finds the statistical distribution function that best fits a data set. It helps to find the best representation of randomness in the model. All variables will be treated as random variables and using the BestFit software, the best distribution of each variable can be obtained.

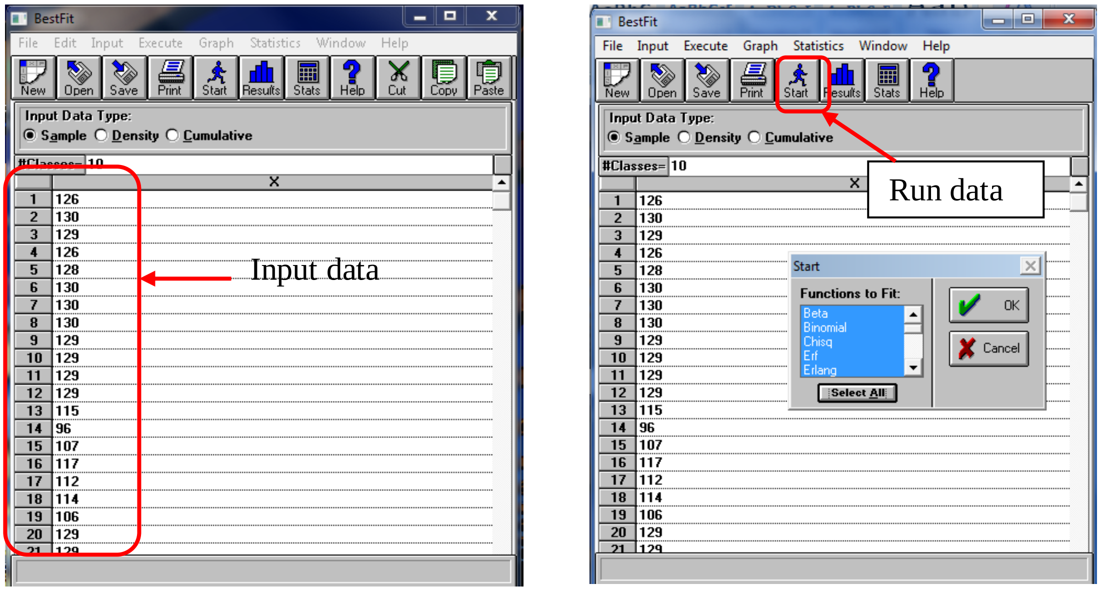


Figure 3.3 Overview on the simulation in BestFit software

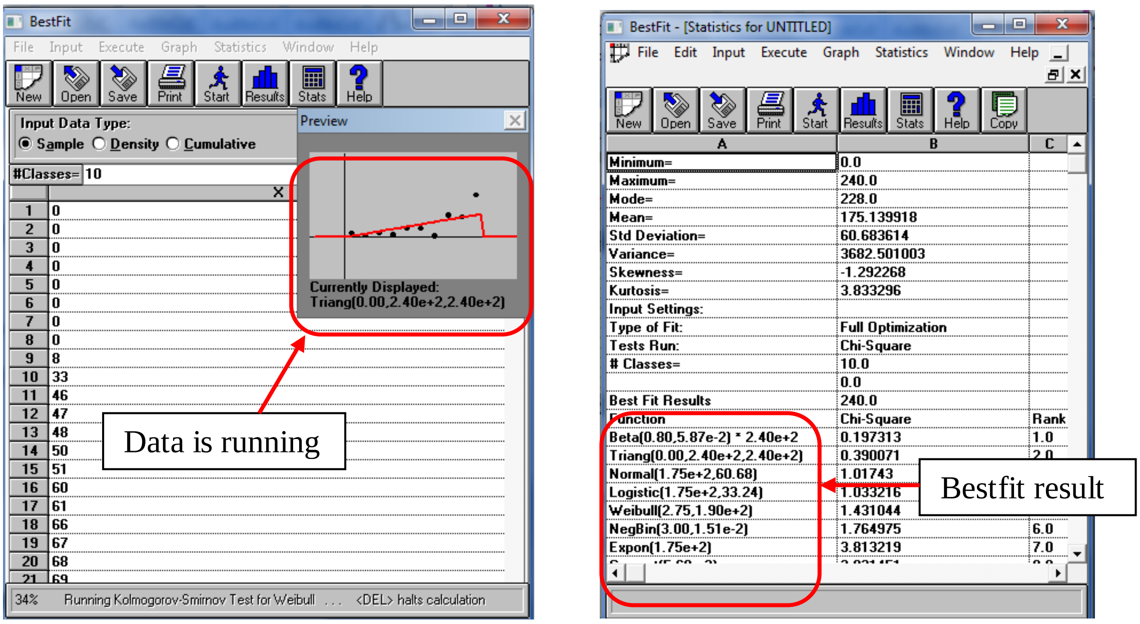


Figure 3.4 Overview on the simulation in BestFit software

3.1.4 Simulation using Variables Processor (VaP) Software

After each of the variables were simulated in BestFit software and their best statistical distribution were obtained, the next simulation was carried out. The characteristics of the best distribution function normally defined by mean (μ) and standard deviation (σ) were used as the main inputs in the Variables Processor (VaP) software.

The VaP software enables the user to deal with non-deterministic quantities, in some given mathematical expression. At first, the limit state function G(X) representing the problem at hand is defined using the usual mathematical notation. The variables then have to be described by choosing among a set of several distribution types. Simulation using Monte Carlo technique is used in order to get the probability of failure of the model defined by the limit state functions earlier. Steps on how to obtain the probability of failure of the system is described below:

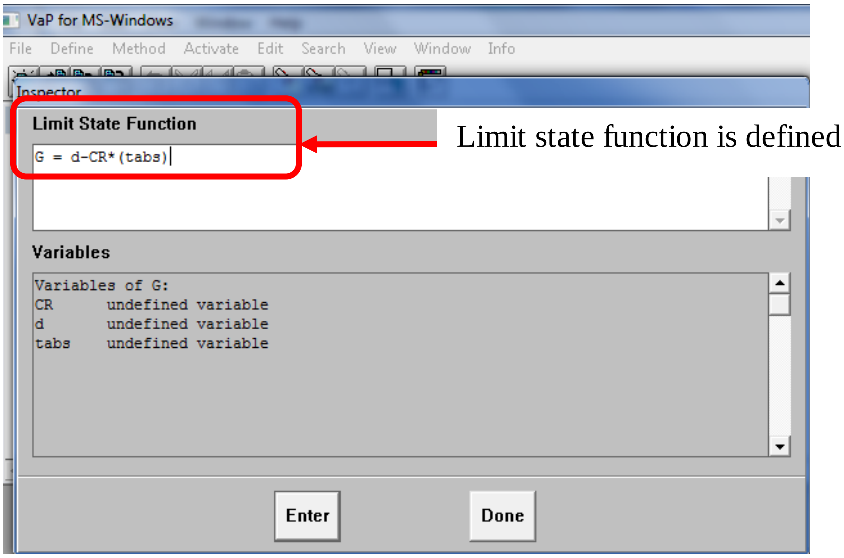


Figure 3.5 Limit State Function is defined

The simulation starts with limit state function that developed earlier is defined in VaP software.

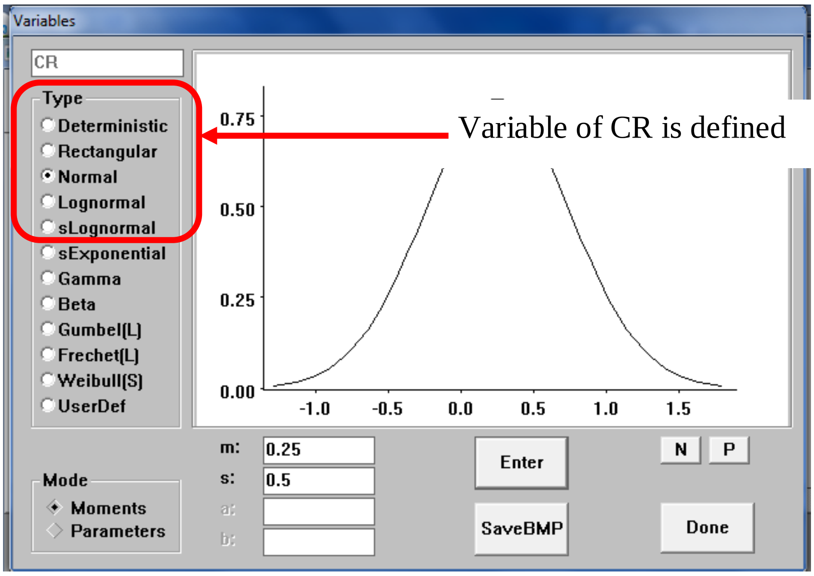


Figure 3.6 The distribution that best fits the data was chosen and input in VaP

After that, the variables in the equation are defined by using the input from BestFit software; mean (μ) and standard deviation (σ)

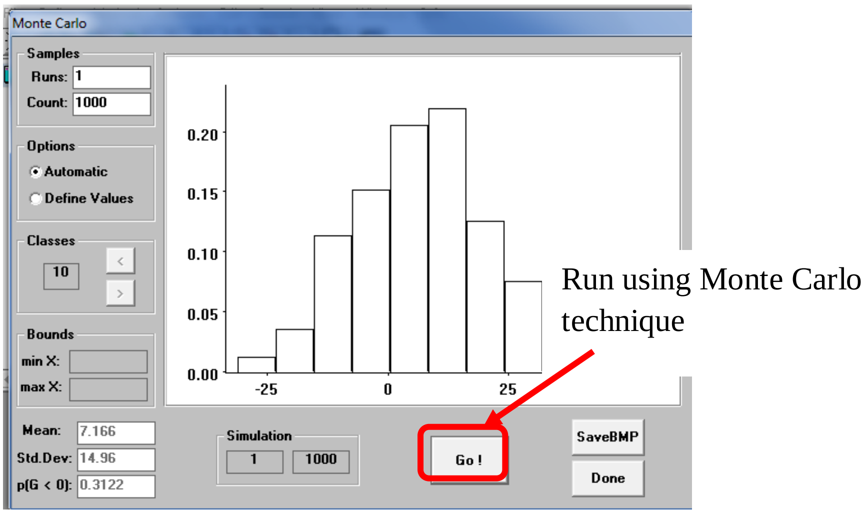


Figure 3.7 Run data using Monte Carlo technique

After all variables have been defined, simulation using Monte Carlo is carried out to obtain the probability of failure of the system.

3.2 TOOLS

The tools required in this research can be divided into two categories namely hardware and software.

- **Hardware**
  1. Personal computer
- **Software**
  1. BestFit Software
  2. Variables Processor (VaP) Software
  3. Microsoft Word
  4. Microsoft Excel
  5. Microsoft Power Point

CHAPTER 4

RESULTS AND DISCUSSION

This section will discuss the simulation trials that have been done and how the data be analyzed.

4.1 SIMULATED CASES

Table 4.1 Different cases with their respective limit state function

Cases	Limit State Function Equations
1	$Z = d - (CR \text{ x } t_{absence})$
2	$Z = d - (CR \text{ x } CI_{injected}/CI_{targeted} \text{ x } t_{absence})$
3	
Model 1	$Z = d - (CR \text{ x } CI_{uniform}/CI_{targeted} \text{ x } t_{absence})$
Model 2	$Z = d - (CR \text{ x } CI_{periodic}/CI_{targeted} \text{ x } t_{absence})$
Model 3	$Z = d - (CR \text{ x } CI_{targeted}/CI_{targeted} \text{ x } t_{absence})$

From the equations of limit state function developed, statistical distribution of each variables were obtained by doing simulation in BestFit software. Results of each model will be discussed in details in the next section.

4.2 CASE 1 RESULTS

From the raw data gathered, simulation using BestFit software was carried out for each variable in the equation. Table below shows the results of the best distributions for each variable along with their values of mean (μ) and standard deviation (σ).

Table 4.2 Input data for BestFit software for Case 1

Variables	Distribution	Mean, μ	Standard deviation, σ
Allowable defect depth, *d*	Normal	15.69	0.76
Corrosion rate, *CR*	Normal	0.25	0.50
$t_{absence}$ (30 days)	Normal	30.42	0.90
$t_{absence}$ (0 days)	Normal	0.42	0.90

In this case, the variable $t_{absence}$ is exploited. The number of days of corrosion inhibitor absence in the pipeline will be decreased from 30 days to 0 days and the effect on the pipeline integrity will be investigated. After the values of mean (μ) and standard deviation (σ) of each variable was obtained, simulation using VaP software was carried out and the results of probability of failure for this case are as tabulated below:

Table 4.3 POF reported according to *tabsence*

$t_{absence}$ (day/month)	Probability of Failure (POF)
30	0.312
28	0.278
26	0.247
24	0.231
22	0.188
20	0.149
18	0.109
16	0.087
14	0.081
12	0.032
10	0.009
8	0.003
6	0.002
4	0.000
2	0.000
0	0.000

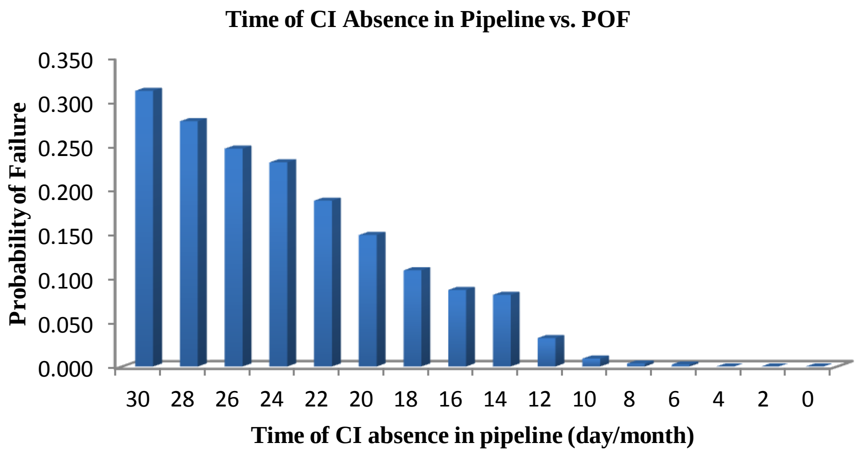


Figure 4.1 POF against time of CI absence in pipeline

From the Table 4.3 and Figure 4.1 above, it can be seen that when the number of days of corrosion inhibitor absence in the pipeline is decreasing, the probability of failure also decreases. It can be concluded that it is very essential for the corrosion inhibitor to be present in the pipeline on a daily basis in order to keep the probability of failure to the lower level.

4.3 CASE 2 RESULTS

In this case, the effect of corrosion inhibitor presence in the system was studied. A comparison was made between Case 1 (without corrosion inhibitor variable in the limit state function) and Case 2 (with the variable of corrosion inhibitor in the system). The main input for simulation in VaP software as below:

Table 4.4 Input data for BestFit software for Case 2

Variables	**Distribution**	**Mean, μ**	**Standard deviation, σ**
Allowable defect depth, *d*	Normal	15.69	0.76
Corrosion rate, *CR*	Normal	0.25	0.5
$t_{absence}$ (30 days)	Normal	30.42	0.90
$t_{absence}$ (0 days)	Normal	0.42	0.90
$CI_{injected}$	Normal	134.12	46.03
$CI_{targeted}$	Normal	175.14	60.68

The results and comparison are tabulated below:

Table 4.5 Comparison of POF between Case 1 and Case 2

$t_{absence}$ (day/month)	POF Case 1	POF Case 2
30	0.312	0.224
28	0.278	0.194
26	0.247	0.178
24	0.231	0.144
22	0.188	0.121
20	0.149	0.116
18	0.109	0.107
16	0.087	0.082
14	0.081	0.058
12	0.032	0.029
10	0.009	0.020

From table above, generally the probability of failure of Case 2 is lower compared to Case 1. Thus, it proves that the presence of corrosion inhibitor does affect the integrity of the pipeline system.

4.4 CASE 3 RESULTS

For Case 3, three different models on inhibitor injection practice were studied in order to find the most optimized maintenance system as stated in the objective.

4.4.1 Model 1

For Model 1, uniformly corrosion inhibitor practice was proposed. In this practice, the amount of corrosion inhibitor injected is uniform throughout the month. The average amount is calculated from the total recommended amount of corrosion inhibitor in a month obtained based on the production rate of the pipeline. The main inputs for VaP simulation are as below:

Table 4.6 Input data for BestFit software for Case 3 (Model 1)

Variables	Distribution	Mean, μ	Standard deviation, σ
Allowable defect depth, *d*	Normal	15.69	0.76
Corrosion rate, *CR*	Normal	0.25	0.5
$t_{absence}$ (30 days)	Normal	30.42	0.90
$t_{absence}$ (0 days)	Normal	0.42	0.90
$CI_{uniform}$	Normal	175.20	42.99
$CI_{targeted}$	Normal	175.14	60.68

4.4.2 Model 2

For Model 2, periodically corrosion inhibitor practice was proposed. The higher amount of corrosion inhibitor needed to be released at the beginning of the month followed by moderate or constant quantity throughout the remaining days (Mustaffa, 2011). This hypothesis was referred to the *physics of corrosion* where the past research shows that corrosion development was higher at the beginning of the time thus more amount corrosion inhibitor is required.

Table 4.7 Input data for BestFit software for Case 3 (Model 2)

Variables	Distribution	Mean, μ	Standard deviation, σ
Allowable defect depth, *d*	Normal	15.69	0.76
Corrosion rate, *CR*	Normal	0.25	0.5
$t_{absence}$ (30 days)	Normal	30.42	0.900337
$t_{absence}$ (0 days)	Normal	0.42	0.900337
$CI_{periodic}$	Normal	175.17	67.828
$CI_{targeted}$	Normal	175.1399	60.68361

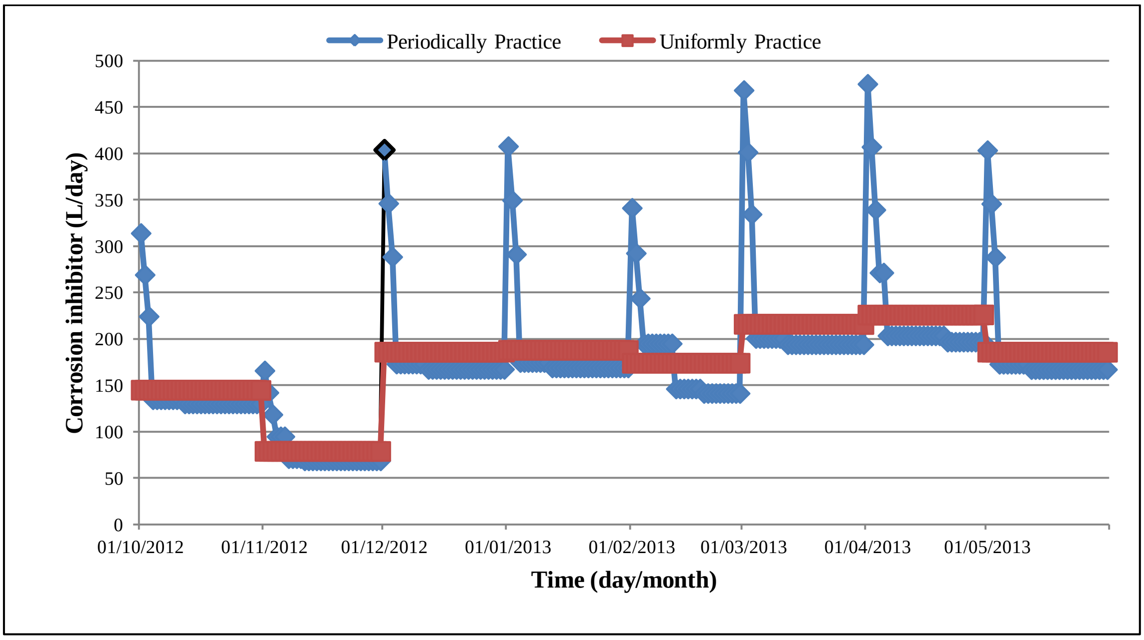


Figure 4.2 Overview of proposed CI practices

Figure 4.2 above shows the overview of proposed corrosion inhibitor practices for Model 1 and Model 2.

4.4.3 Model 3

For Model 3, the injection practice was carried out according to the recommended amount of corrosion inhibitor calculated from production rate of the pipeline system.

Table 4.8 Input data for BestFit software for Case 3 (Model 3)

Variables	**Distribution**	**Mean, μ**	**Standard deviation, σ**
Allowable defect depth, *d*	Normal	15.69	0.76
Corrosion rate, *CR*	Normal	0.25	0.5
$t_{absence}$ (30 days)	Normal	30.42	0.90
$t_{absence}$ (0 days)	Normal	0.42	0.90
$CI_{targetd}$	Normal	175.14	60.68
$CI_{targeted}$	Normal	175.14	60.68

From these three different models proposed, the simulation using Monte Carlo technique is carried out in order to get the probability of failure of each model. The model with lowest value of probability of failure seems to be the most optimized maintenance system for corrosion inhibitor injection. Table below summarized findings from simulations carried out:

Table 4.9 Summarized POF according to 3 cases developed

Model 3	**POF**
Case 1 (Uniform)	0.05
Case 2 (Periodic)	0.0444
Case 3 (As Target)	0.0533

Results in the table seemed to favor in the periodically practice better with the smallest probability of failure value of 0.0444. From this simluations, it can be concluded that different injection practice does affect the pipeline integrity even though the values are slightly different with each other.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

There are many ways that could be done in optimizing corrosion inhibitor in the pipeline. This research was meant to find the most optimized maintenance system by applying the knowledge from physics on corrosion growth. It is important to highlight here that each corrosion grows in the pipeline is considered the big threat to the oil and gas industry which finally might lead to failure. From the simulation carried out, it is proven that the presence of the corrosion inhibitor does affect the integrity of a pipeline. Thus, it is essential and recommended for the pipeline operators to keep the corrosion inhibitor in the pipeline on daily basis.

In the above simulation results, it could be speculated that the periodically corrosion inhibitor practice model will be able to sustain the pipe wall structure better compared to the other two model as it carries the lowest probability of failure value. The outcome from this research could be used to educate pipeline operators on how corrosion inhibitor injection practice should be carried out because corrosion inhibitor is believed to be the most-effective way to control this major threat in pipeline operation. Based on the historical operations in year 2009 and year 2012 of one of the corroded pipeline in Malaysian waters, reliability models were developed and the most optimized maintenance system was proposed. Hence, objectives of this research were achieved.

This research could be improved by incorporating cost impact study on the optimized corrosion inhibitor practice models in order to obtain the best model that optimizes both in terms of maintenance and cost. It is also advisable for the pipeline operators to keep their injection practice database updated so that different production profiles could be modeled for a better reference in the future.

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