FINAL YEAR PROJECT REPORT

Offshore Pipeline Reliability Assessment Using Degradation Analysis and P-F Interval Model

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CERTIFICATION OF APPROVAL

OFFSHORE PIPELINE RELIABILITY ASSESSMENT USING DEGRADATION ANALYSIS AND P-F INTERVAL MODEL

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Approved

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CERTIFICATION OF ORIGINALITY

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

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(MOHD AMRI BIN MOHAMMAD NOOR)

ABSTRACT

Offshore pipeline plays an important role in oil and gas industry. It is considering as the most favored transportation mode of crude oil in large quantity. Throughout the years, there are a lot of pipeline accidents caused by metal cross section losses due to the internal corrosion. Therefore, pipeline operators have practiced reliability-based corrosion management programs which consists three components in managing their pipeline which are in-line inspection, pipeline reliability evaluation and pipeline repair.

In order to determine the pipeline reliability, there are two approaches that practiced which are deterministic method and probabilistic method. ASME B31.G and P-F interval model are example of deterministic approach. Meanwhile, degradation analysis is the example for probabilistic approaches in determining the remaining pipeline life.

This study explores both methods applied on offshore pipeline by using Intelligent Pigging (IP) inspection data. The objective of this study is to determine the offshore pipeline remaining life using PF-interval model and degradation analysis. The result from both methods is compared with the result generated by ASME B31.G. The result showed that degradation analysis more conservative than ASME B31.G and P-F interval since it was provide shorter mean life period.

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ABBREVIATIONS

ASME	American Society of Mechanical Engineers
MAOP	Maximum Allowable Operating Pressure
MFL	Magnetic Flux Leakage
POF	Probability of Failure
SRB	Sulphide Reducing Bacteria
UT	Ultrasonic Testing
H2S	Hydrogen Sulphide
MIC	Microbiologically Induce Corrosion
IP	Intelligent Pigging
ICR	Internal Corrosion Rate
TTF	Time To Failure
NA	Not Available
FFS	Fitness For Study
PITT	Pitting Corrosion
GENE	General Corrosion
EXSL	Axial Slotting Corrosion
AXGR	Axial Grooving Corrosion
CISL	Circumferential Slotting Corrosion
CIGR	Circumferential Grooving Corrosion

CHAPTER 1
INTRODUCTION

1.1 Background of Project

Offshore pipeline plays an important role in oil and gas industry. It is considered as the most favored transportation mode of crude oil in large quantity. It represents a high capital investment and functions as blood vessels serving to continuity of crude oil supply to the oil and gas industry [1]. In fact, it has the highest capacity and the least environmentally disruptive form for transportation for crude oil. Pipeline operators has invested large amount of money in managing the pipeline to ensure the pipeline service availability for the continuity supply of crude oil. Therefore, the pipeline failure will cause the shortage supply of crude oil and affects the economic globally. The price of crude oil will increase exponentially and give huge impact to related industry such as automotive, manufacturing and energy.

Based on statistics, offshore pipeline has good performance in transporting crude oil; however, their increasing age has raised concerns among pipeline operators. They are typically operated in deteriorative environment that cause corrosion and impact the integrity of pipeline [2]. The corrosion is a major potential problem and it becomes worse as the pipeline age. Therefore, pipeline operators throughout the world are confronted with expensive and risk task of operating aged pipeline because of corrosion and its potential damaging effects. The major effect of corrosion is the loss of metal cross section. This results in a reduction of pipeline carrying capacity and safety [3].

There are a lot of pipeline accidents caused by metal cross section losses due to the internal corrosion over the world. One of the incidents was the crude oil leak at Yellowstone River in Montana, US [4]. An underwater pipeline ruptured and released about 1000 barrels of crude oil into the river. The rupture had caused a 40 km trail that stained the riverbank and prompted temporary evacuations of residents along the 32 km stretch. Meanwhile in 2010, a worse pipeline incident was recorded at Kalamazoo River [5]. Based on the investigation report, the pipeline had badly corroded in 2005, but the pipeline operator failed to perform pipeline repair as preventive action from pipeline rupture. As a result, the incident caused the most expensive oil spill in US history with cleanup costs exceeding 800 million USD.

Pipeline operators have realized they have to face the hazardous consequences of pipeline failure especially to the environment. In fact, they have to maintain the pipeline service availability to ensure the continuous of crude oil supply. In order to overcome this problem, pipeline operators have practiced reliability-based corrosion management programs which consists three components in managing their pipeline which are in-line inspection, pipeline reliability evaluation and pipeline repair [7].

In order to determine the pipeline reliability, there are two approaches that practiced which are deterministic method and probabilistic method. ASME B31.G and P-F interval model are example of deterministic approach. Meanwhile, degradation analysis is the example for probabilistic approaches in determining the remaining pipeline life. Among those approaches, ASME B31.G is the most common approach that practiced by pipeline operators. Both approaches, deterministic and probabilistic approaches use the pipeline remaining wall thickness data from the in-line inspection to estimate the remaining pipeline life. However, due to inherent uncertainties in the corrosion process and in operating conditions, probabilistic are widely acknowledged than deterministic approaches [8].

In this study, the methods, namely degradation analysis and P-F interval, are being explored using intelligent pigging (IP) data. Degradation analysis has been widely used in reliability analysis of piping. However, the application to offshore pipeline by using intelligent pigging (IP) data is limited. The results are compared to ASME B31.G which is normally being used by most pipeline operators.

1.2 Problem Statement

Pipeline operators have focused on reliability study prior pipeline maintenance planning to minimize pipeline failure risk. The deterministic approach, ASME B31.G and P-F interval has become main choice for them in determining the pipeline remaining life. However, the approaches, the associated parameter assumed to be free from any uncertainty which different in reality. The load and resistance parameters show some degree of variability in their value and raise some uncertainties in the resistance of a pipeline. Moreover, this approach cannot provide any quantitative information about the probability of failure of a pipeline with time [3]. Therefore, the assessment result could not describe the actual situation of the pipeline and may overly conservative at times [10].

To deal with these problems, degradation analysis was used to assess the reliability and predict the remaining life of an offshore pipeline. The wall loss information is the main data input for the degradation analysis. This analysis has been applied a lot in piping reliability assessment. Since the intelligent pigging (IP) data were able to provide the wall loss information of offshore pipeline, the degradation analysis can be extending its application to offshore pipeline.

1.3 Objective and Scope of Study

The objective of this project is to determine the offshore pipeline remaining life using PF-interval model and degradation analysis. The result from both methods is compared with the result generated by ASME B31.G.

The study has been done within several scope of study. The details scopes of study for this study were shown as follow:

1. The study has been applied to offshore pipeline which located on seabed.
2. The IP inspection data from year 1993, 1997, and 2009 were used as main data for this study.
3. The wall loss information from IP data has been used as main data input for the study.
4. The study is only consider defects between 10% wall loss until 80% wall loss as main data input [11].
5. The study is only considered internal corrosion defects because it is the main failure contributor to offshore pipeline.
6. The study has been focused on general corrosion defects only, for the comparison purpose with ASME B31.G which also focused on the same type corrosion defect.
7. The study only focused on defects recorded from Zone 2 area, which is about 5 km from offshore platform since this area is the highest weightage in risk analysis that specified by the pipeline operator [12].

CHAPTER 2
LITERATURE REVIEW

2.1 Offshore Pipeline System

During 1870s, crude oil was transported by wooden barrels. As the volume was increased, pipelines were used as main transportation mode to transport crude oil [13]. Offshore pipeline system consists of several important components which is receiver and launcher for pigging facilities, subsea pipeline, and riser [14]. Subsea pipeline is a primary horizontal pipe lying on, near or beneath the seabed. Meanwhile, receiver and launcher are pipeline facilities for pigging activity purpose. The section from pipeline bend at the sea bed until the receiver is defined as riser [15].

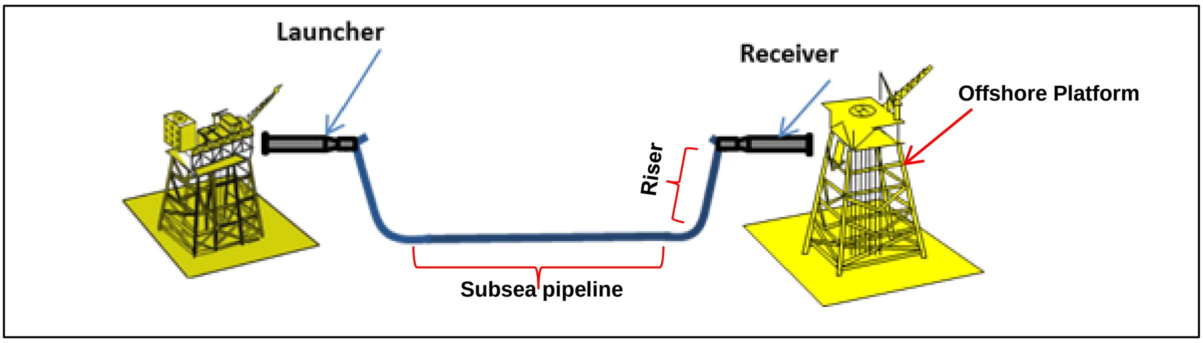

Figure 1 : Offshore Pipeline System [14]

Pipelines have a good safety record in transporting crude oil in oil and gas industry. This is due to a combination of good design, materials and operating practice. However, like any engineering structure, pipelines do occasionally fail. The most common cause of damages and failure is corrosion.

2.2 Offshore Pipeline Failure Mode

Corrosion is an electrochemical process. It is a time dependent mechanism and depends on the local environment within or adjacent to the pipeline. The transmitting crude oil may carry corrosive elements such as water, carbon dioxide, hydrogen sulfide, and sulphate reducing bacteria [16].

Usually, the major contributors for corrosion to happen inside the pipeline are acid gases of Carbon Dioxide (CO_2) and Hydrogen Sulphide (H_2S). Both gases will dissolve in water that accumulate inside pipeline and dissociate causing possible carbonate acid corrosion and hydrogen sulphide which lead to corrosion. In fact, the presence of water inside pipeline is a pre-requisite for a corrosion to take place. Carbon dioxide dissolves in water and dissociates to form week carbonic acid which causes corrosion.

Meanwhile, when H_2S is dissolved in water, the resultant acid will react with pipeline wall, producing iron-sulphide, with a corresponding cathodic reaction that generates hydrogen. The hydrogen tends to diffuse into the steel where it can cause cracking in susceptible microstructures [17]. The corrosion initiates metal loss defect which may be distributed in the radial, circumferential and axial directions. In general, the metal loss defects are defined by a length (*L*) and through wall thickness depth (*d*). The defect profile is idealized rectangular or parabolic geometric shapes [18]. The defects form a region of stress concentration, thereby interrupting the Normal hoop force trajectories along its length and depth. The primary failure mechanism is considered to be extension of the defect through the remaining portion of the pipeline wall. The type of failure is depending on the size of the resulting through-wall defects or metal loss defects [19].

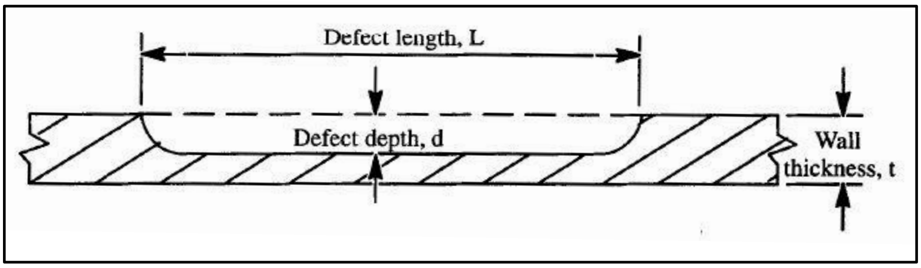

Figure 2 : Corrosion defect parameter [19]

At an active corrosion defects, pipeline may fail by small leak or burst. Small leak occurs when the defects penetrates the pipeline. Meanwhile, burst occurs when the pipeline wall undergoes plastic collapse due to internal pressure at the defects location. A burst can be classified as a rupture or large leak [20]. Moreover, as result of the exposure and operation, corrosion tends to appear and cause pipeline metal losses become worst. With increasing time, the pipeline level of safety and reliability decrease and cause will cause pipeline failure [21].

Pipeline failure will conveying dangerous substances and can pose major risk. Release of flammable and toxic materials can be the initiating events of accident with catastrophic effects, public tolerance to environmental pollution and accidents [22].

2.3 Offshore Pipeline Reliability – Based Corrosion Management

The huge impact of pipeline failure has become main concern to the pipeline operators. Therefore, the reliability-based corrosion management program is being increasingly used by pipeline operators. This program is typically include three task, namely high resolution in-line inspection (intelligent pigging) to detect and size the corrosion defects, failure probability evaluation of the pipeline based on the inspection results and mitigation of the defects [23]. Among those three tasks, the assessment of corrosion defects is the most crucial part. The assessment is not straightforward task since subsea pipeline lying on seabed, thus are inaccessible for direct inspection. Therefore, in-line inspection tools, such as “smart pigs” or “intelligent pig” has been develop to perform in-service inspection of subsea pipeline to collect information about corrosion defects in term of pipeline wall loss percentage [24].

“Intelligent Pigs” are cylinder-shaped electronic devices used by pipeline operators to detect any loss of metal in the pipeline. The device will insert into the pipeline, propelled by pipeline fluid and record physical data about pipeline integrity as it moves through the pipeline. Intelligent pigs have evolved into three types, which are metal loss tools, crack detection tools, and geometry tools. Metal loss tools will provide the corrosion defect information along the pipeline. Thus, it is the most important tool in assessing the pipeline current integrity.

Metal loss tools can be categorized into several specialized “intelligent pig”. The common specialize “intelligent pigs” used by pipeline operators is magnetic flux leakage tools (MFL) and ultrasonic tool (UT). Magnetic flux leakage tool will induce a magnetic field to the pipeline. As it travels, it locates and records magnetic flux anomalies in the pipeline. The recorded magnetic flux data is converted information that provides an indication of metal loss in the pipeline.

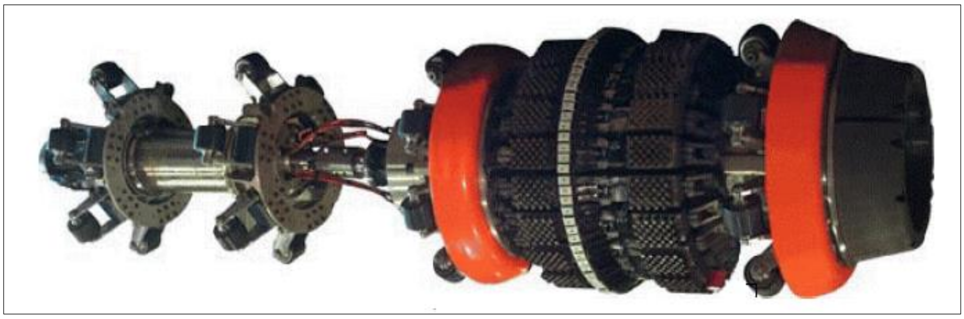

Figure 3 : A typical MFL tool pig [25]

Most of MFL tools can determine the location and o'clock position of the metal loss anomaly and specific either the anomaly is internal or external to the pipeline wall. In addition, it also provides data for each corrosion anomaly including its length and maximum depth, which required in calculation of pipeline remaining strength [1].

Meanwhile, an ultrasonic tool (UT) provides similar physical pipeline data as MFL tool, but it uses ultrasonic technology. This tool uses the principle of ultrasonic to determine the remaining pipeline wall thickness. During the inspection, the piezo electric transducer attached to the tool sends out a short pulse of ultrasonic energy which is initially reflected from the internal surface of the pipeline wall. However, not all the energy is reflected, about half of the energy penetrates the pipeline wall and reflected back from the outer pipeline wall. The time of flight for the energy to reflect back will provide the quantitative values for the distance between the sensor and internal wall. Therefore, the remaining wall thickness can be determined [26].

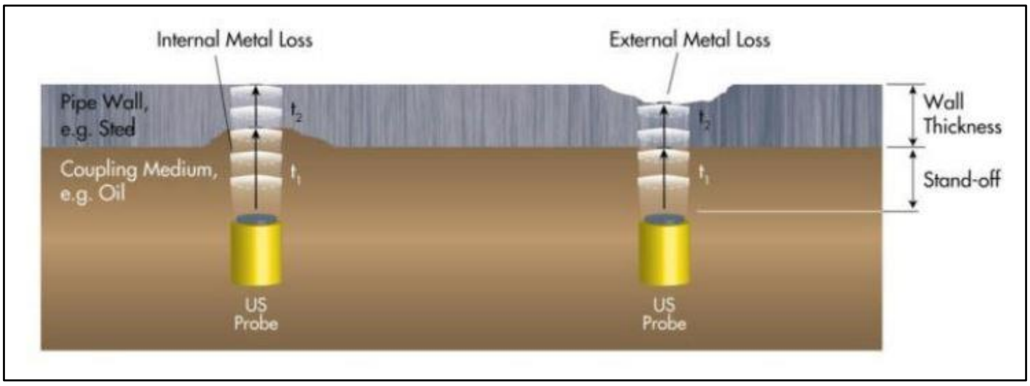

Figure 4 : The working principle of ultrasonic tools [26]

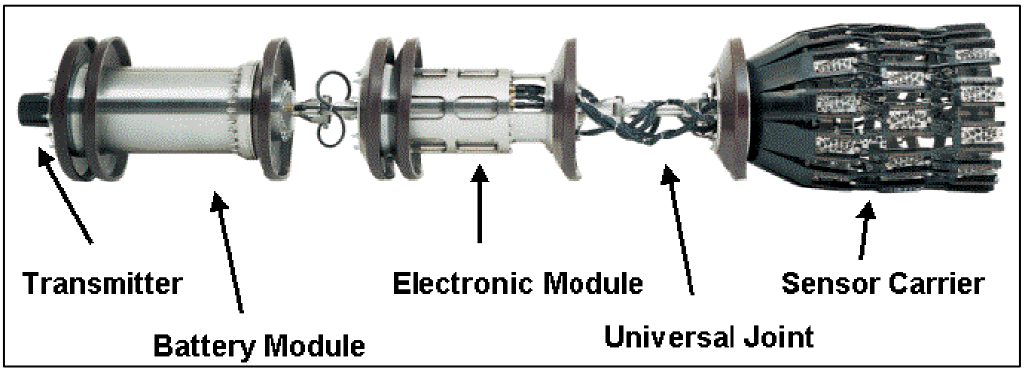

Figure 5: Smart Pig with ultrasonic tool [26]

Although the MFL and ultrasonic tool using difference working mechanism, both tool provide the metal loss detection information of pipeline. They provide the metal loss information such as metal loss dimension, length, width, depth and location for every recorded defect. The defect dimension data is very essential in pipeline reliability and fitness for service pipeline study. Therefore, the in-line inspection is very crucial in reliability-based corrosion management program.

2.4 Pipeline Reliability Assessment

In reliability –based corrosion management program, assessing the pipeline integrity is an important matter. There several method to assess the pipeline reliability and integrity. The conventional method is using the hydro test or hydrostatic test. This test will pressurize the pipeline close to the failure pressure. However, this test has some serious drawback such as failure phenomena known as “reversal” may occur. This implies that a corroded pipeline may survive a hydrotest at certain pressure, close to the failure strength, but may subsequently fail at a pressure significantly lower than the pressure it had previously survived. Therefore, revalidation by a hydrotest does not offer an absolute guarantee of a corroded pipeline’s integrity [27].

Nowadays, to overcome that problem, most of pipeline operators used IP) inspection data as main reference in assessing their pipeline reliability and integrity. Usually, they will do reliability in order to get remaining life of offshore pipeline. The common method in reliability assessment of offshore pipeline is ASME B31.G. This method used wall loss information from intelligent pigging (IP) data to determine offshore pipeline remaining life [11].

2.5 ASME B31.G Mathematical Model

Among the available technique, ASME B31.G is most widely used and accepted technique. Through the experimental investigation, the remaining strength estimate obtained from this technique show satisfactory for pipeline with corrosion defects [3]. In this technique, the failure pressure is determine based on the defect information and compared with the Maximum Allowance Operating Pressure (MAOP). The failure pressure can be calculated based on the Eq. (2) and Eq. (3) [11].

$$Corroded\ Area, A\ = 0.893\sqrt{\frac{L_m}{\sqrt{Dt}}} \tag{1}$$

where, D = Outside nominal diameter, in.

t = Pipeline wall thickness, in

L_m= measured longitudinal extent of the corroded area, in.

For Values of A less than or equal to 4.0, the failure pressure is calculates by using Eq. (2).

$$P_{failure} = 1.1P\left[\frac{1-\frac{2}{3}\left(\frac{d}{t}\right)}{1-\frac{2}{3}\left(\frac{d}{t\sqrt{A^2+1}}\right)}\right] \tag{2}$$

where, d = maximum defect depth, in.

t = Pipeline wall thickness, in.

L = defect length, in.

P = the established MAOP

For values of *A* more than 4.0, the failure pressure is calculates by using Eq.(3).

$$P_{failure} = 1.1P\left[1 - \frac{d}{t}\right] \quad (3)$$

where, d = maximum defect depth, in.

t = Pipeline wall thickness, in.

P = the established MAOP

Based on the Eq. (2) and Eq. (3), the defect dimension is the major contribution to the internal failure pressure of pipeline. The defects with high depth, width, and length of the make the internal failure pressure became lower and cause the lower pipeline reliability. However, this method only concern with estimation of present remaining pipeline strength at some point, not in future.

From the pipeline operator's perspective, the prediction pipeline strength in future would be useful to estimate the safety future operation of the pipeline. It will eliminate the need for costly operations such as continuous monitoring, frequent remaining strength evaluation and unnecessary repair. Therefore, to deal with these problems, reliability technique can be used to assess the reliability and remaining pipeline life [3]. The result can be used to prepare effective and economic inspection, repair, and replacement operation. ASME B31.G is a deterministic approach in determining the reliability offshore pipeline. Another example is P-F interval model. Both method uses wall loss information as main data in assessing the offshore pipeline reliability.

2.6 PF-Interval Model

P-F interval model is one of the method that commonly adopted by pipeline operator to predict pipeline reliability. Usually, pipeline is exposed to random shock or event. When a shock occurs, it's produced a weakness, a potential failure and will develop into critical failure. The shock cannot be observed, however the potential failure is revealed after the shock happen. The potential failure is noted as "P" and "F" will be the point of time where the pipeline has functionally failed [30]. The point "P" will continue to deteriorate with accelerating rate until its reach the point of functional failure "F". The behavior how the potential failure deteriorate can be illustrates as P-F curve in the Figure 6 [31].

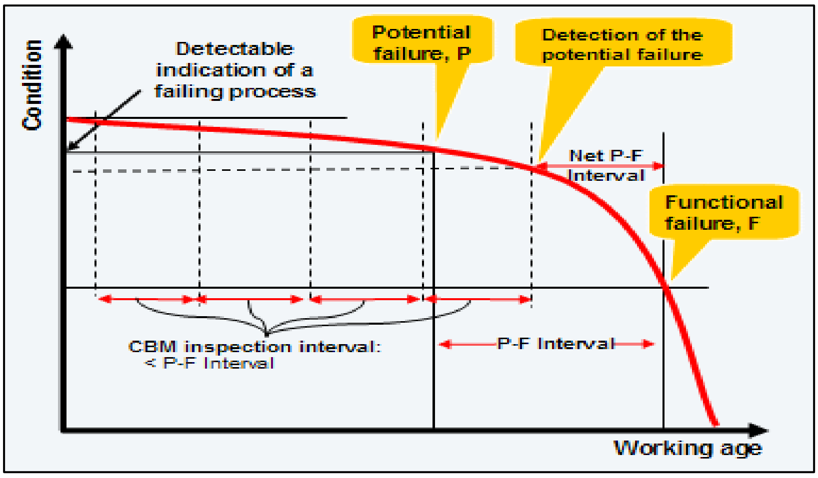

Figure 6 : The P-F curve [31]

For the offshore pipeline, the potential failure "P" is state by detection of the 10% pipeline wall loss. Meanwhile, functional failure is considered as 80% of pipeline wall loss [11]. The time taken for potential failure "P" to deteriorate until functional failure "F" is called P-F interval period. This interval could give information on how often on conditional. Practically, the inspection interval must be less than the P-F interval period so that the potential failure can be detected and repaired. On other hand, if the inspection interval is longer than the P-F interval period, there is a chance to miss the failure detection. Therefore, it is sufficient to select an inspection task frequency equal to half of the P-F interval [31].

Since P-F interval provide optimum inspection interval period task, the model is frequently used in the maintenance optimization plan especially for subsea pipeline. The model can determine how much the remaining pipeline life after a potential failure “P” is detected. This remaining life information is useful for the pipeline maintenance planning [32]. However, in this approaches, the associated parameter assumed to be free from any uncertainty which different in reality. This approach cannot provide any quantitative information about the probability of failure of a pipeline with time [3]. To deal with these problems, degradation analysis can be uses to assess the reliability and predict the remaining life of an offshore pipeline.

2.7 Degradation Analysis Model

Degradation analysis is one available method to assess the reliability of offshore pipeline. Typically, mean time between failure (MTBF) is the common metrics to describe the reliability of the equipment or a system [34]. However, from pipeline operators experience's, assessing the pipeline reliability based on MTBF measurements are often hindered by lack of observed piping failures. What is usually available is a collection of degradation data which is the measurement of pipeline wall loss taken during inspection.

Degradation analysis is useful for the analysis of failure time distribution in reliability study. The analysis involves the measurement and extrapolation of degradation data that can be directly related to the failure [35]. A level of degradation at which a failure is said to have occurred needs to be defined first. For this study, the failure is defined as the wall loss recorded from inspection reach the maximum degradation which is 80% wall loss [11]. To perform the degradation analysis, the extrapolation can be done by several models, which are linear model, exponential model, power model, and logarithmic model. For this study, the growth of a corrosion defects with increased expose period is dependent primarily on the characteristic of the pipeline material, properties of the fluid being transport and the surrounding environment. Since the growth rate can be approximated by a steady state rate, the linear degradation model is reasonable [3]. The linear degradation model is shown by Eq. (4) [35].

$$y = ax + b \tag{4}$$

where $y = current\ wall\ thickness$

$x =$time taken

$a =$degradation rate

$b =$nominal wall thickness

The linear degradation model is used to determine the time to failure for each defects. The time to failure data can be used in life data analysis [35]. Life data analysis is one of the well-known engineering tools for analyzing failure data. The technique has application in wide range of industries such as military, automotive, electronics, and aerospace.

There are several life time distributions that have been successfully served as population models for failure such as Normal, Weibull, Gamma and Gumbel. The details of the distribution are as shown in the Table 1 [36].

Table 1 : The key formula for Weibull, Normal, Gamma and Gumbel distribution

Lifetime distribution	**PDF**	**CDF**	**Hazard Rate**
Weibull	$f(t) = \frac{\beta}{t}\left(\frac{t}{n}\right)^{\beta} exp\left[-\left(\frac{t}{n}\right)^{\beta}\right]$	$F(t) = 1 - exp\left[-\left(\frac{t}{n}\right)^{\beta}\right]$	$h(t) = \frac{\beta}{n}\left(\frac{t}{n}\right)^{\beta-1}$
Normal	$f(t) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(t-\mu)^2}{2\sigma^2}}$	$F(t) = \int_{\infty}^{t} \frac{1}{\sigma\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{\tau-\mu}{\sigma}\right)^2\right] d\tau$	$h(t) = \frac{\emptyset \frac{t-\mu}{\sigma} / \sigma}{R(t)}$
Gamma	$f(t) = \frac{t^{y-1}}{\theta^{\gamma}\Gamma(\gamma)} e^{\frac{-t}{\theta}}$	$F(t) = 1 - e^{\frac{-t}{\theta}\sum_{k=0}^{n-1}\frac{\left(\frac{t}{\theta}\right)^k}{k!}}$	$h(t) = \frac{\frac{1}{\theta}\left(\frac{t}{\theta}\right)^{n-1}}{(n-1)!\sum_{k=0}^{n-1}\frac{\left(\frac{t}{\theta}\right)^k}{k!}}$
Gumbel	$f(t) = e^{-(x+e^{-x})}$	$F(t) = e^{-e^{-(x-\mu)/\beta}}$	$h(t) = \frac{e^2}{\sigma}$

In life data analysis, the mean life is determined by analyzing time to failure data. Therefore, the degradation analysis model is able to calculate time taken for each defect to degrade until the maximum limit value. Based on the time to failure for each defects, the remaining mean pipeline life is able to be determined.

CHAPTER 3
METHODOLOGY

The project has been done by using two model, degradation analysis model and PF-interval model using in Weibul++ software. This analysis used time to failure (TTF) for each defect as main input data. Meanwhile, for PF-interval model the remaining wall thickness of same defect point from first inspection until last inspection has used as main data input in the software. The overall of work flow for both approaches are clearly as shown in Figure 7.

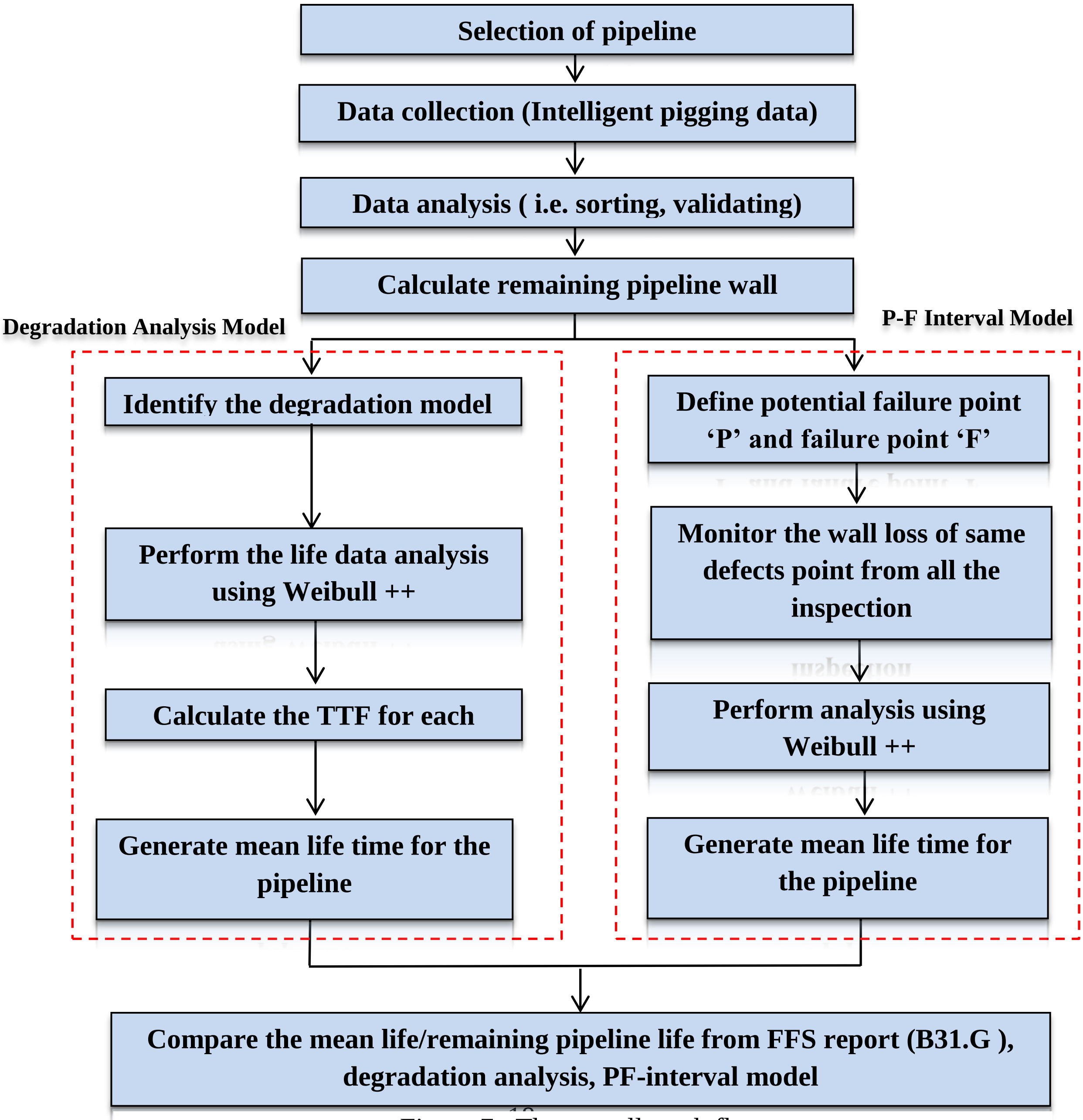

Figure 7 : The overall work flow

3.1 Degradation Analysis Model

Step 1: Selection of pipeline

The selection of pipeline has been made by considering several criteria in order to make sure the pipeline have sufficient data for the analysis. First, the selected pipeline should have minimum 3 inspection data to ensure the data has represented enough of the actual pipeline condition. The inspection data should be reliable to be used for the analysis. Lastly, the pipeline should have conducted Fitness For Service (FFS) for comparison purpose at the end of this study.

Step 2: Data collection

The data collection phase includes the data gathering for pipeline Intelligent Pigging (IP) inspection raw data, design data and Fitness For Study (FFS) report. From the IP inspection data, only the absolute distance, defect depth, and defect corrosion type was extracted for the input data. Meanwhile, pipeline design life, pipeline nominal wall thickness, pipeline installation year were collected from the design data. The details about design data, FFS report and IP raw data has clearly shown in the appendix.

Step 3: Data analysis

The inspection data was sorted by considering only internal corrosion defects, general corrosion defect type and defect from pipeline zone 2. Based on ASME B31.G, only defects depth between 10% until 80% of pipeline wall loss has been considered in this study [14].

Step 4: Remaining pipeline wall thickness calculation

The inspection data provided wall loss information for each defects in term of wall loss percentage. A simple calculation had to be done to get actual remaining pipeline wall thickness. The Eq. (5) is used for the calculation.

$$remaining\ wall\ thickness = wt - ((\frac{d}{100}) \times wt) \tag{5}$$

where: *wt* = nominal wall thickness in mm

d = percentage wall loss

Step 5: Identify Degradation Model

The corrosion defect inside the pipeline has stabilized to a steady state. Therefore, the linear growth approximation was reasonable. Based on the degradation model, Eq. (6), the degradation rate for each defect was able to determine.

$$y = ax + b \tag{6}$$

where y =current wall thickness

x = time taken

a =degradation rate

b =nominal wall thickness

Step 6: Perform life data analysis

The time to failure data for each defect has been calculated in step 6. By using life data analysis in Weibul ++, the time to failure for all defects has been extrapolated to fit several distribution. The result for each distribution was present in the result and discussion section. The failure rate and mean life from the best distribution were selected to be compared with ASME B31.G method.

Step 7: Generating the failure rate and pipeline mean life

After the extrapolation in Weibul ++, the graph of reliability function and probability of failure can be generated. By using quick calculation pad function in the software, the pipeline mean life and failure rate can be estimated. In this case, the mean time to failure was taken as pipeline remaining life.

3.2 P-F Interval model

Step 1: Define ‘P’ and ‘F’

The ‘P’ and ‘F’ for this project had been identified by referring ASME B31.G Manual for Determining the Remaining Strength of Corroded Pipeline [11]. The potential failure ‘P’ is identify as 10% of pipeline wall loss and 80% pipeline wall lost for the failure ‘F’. This ‘P’ and ‘F’ later will use as threshold parameter in Weibull ++ during develop the PF – interval model.

Step 2: Monitor the wall loss of same defects point from all the inspections

All the defects that recorded in first inspection were monitored in the next inspection. The absolute distance for each defect was used as reference in tracking the recorded defects during first inspection in next inspection data. The details of the data input as shown in the Table 2.

Table 2 : The data input for P-F interval model

Defect points	Absolute Distance, m	Inspection 1993		Inspection 1997		Inspection 2009	
		Operating period, year	Wall loss percentage, %	Operating period, year	Wall loss percentage, %	Operating period, year	Wall loss percentage, %
1	4720.70	16.52	15.00	21.02	18.00	32.69	27.00
2	5409.90	16.52	15.00	21.02	23.00	32.69	29.00
3	41363.04	16.52	15.00	21.02	18.00	32.69	33.00

Step 3: Perform degradation analysis

The wall loss information from each inspection regarding the 3 defects points were used as main data input in this analysis. Next, the potential failure ‘P’, 10% of wall loss from nominal wall thickness selected as minimum threshold. The failure point ‘F’, 80% loss from nominal wall thickness was selected as maximum threshold in this analysis.

Step 4: Estimate the P-F interval

After the wall loss data for 3 defect points from each inspection completed inserted in the Weibull ++, the linear degradation model was selected in the analysis [3]. Then, the graph of degradation can be generated. Based on the degradation graph, the P-F interval period has been calculated.

Step 5: Compare the pipeline remaining life

After degradation analysis and PF-interval model completed, mean life time has been taken as pipeline remaining life time. The remaining pipeline life from degradation analysis, P-F interval and ASME B31.G has been compared.

CHAPTER 4
RESULT AND DISCUSSION

4.1 P-F interval Model

The P-F interval model has been applied to an offshore pipeline. The pipeline has been inspected three times, in 1993, 1997, and 2009. It has been operated for 36 years old since its installation in year 1977. During first inspection, only 3 defects point recorded. Then, these 3 defects point has been observed in next inspection. The wall loss percentage from each inspection has been taken as main data input in degradation analysis using Weibull ++ software. The details result of P-F interval model were shown in the Table 3.

Table 3 : The result of P-F interval model

Defect points	Absolute Distance, m	Time to reach potential failure (P), year	Time to reach failure (F), year	P-F Interval	Pipeline remaining life (PF period - operating period up to 2009 year)	pipeline remaining life from FFS (ASME B31.G)	Year different
1.00	4720.70	10.46	80.29	69.83	37.83	35.00	5.83
2.00	5409.90	9.64	85.70	76.06	44.06	35.00	9.06
3.00	41363.04	11.27	95.20	83.93	51.93	35.00	16.93
Average				**76.60**	**44.6**	**35.00**	**10.6**

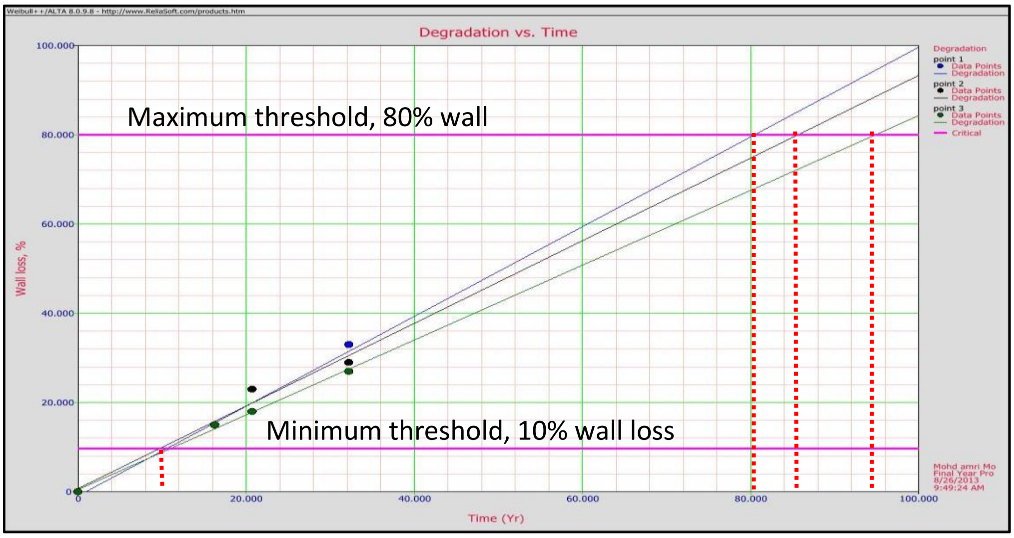

Figure 8 : The graph of P-F interval model

The P-F interval model has been applied by using intelligent pigging data (IP) as shown in the Table 2. Using Weibull ++ software, the graph of wall loss with respect of exposure time has been plotted as shown in the Figure 8. The time taken for the degradation to reach potential failure, 10% of wall loss and failure, and 80% of wall loss can be estimated. The details of time taken to reach 10% and 80% of wall loss clearly showed in the Table 3.

Based on the Table 3, the defect point 1 took 10.46 years for the defects to grow about 10 % of wall thickness loss. Then, the defect will continue to grow until its reach 80% of wall thickness loss 80.29 years later. Thus, for the P-F interval f defect point 1, the duration was taken from its reach 10% until 80% of wall loss which is 69.83 years. In order to determine the remaining life for based on the defect 1, the P-F interval need to be minus the operating period which is 32 years. Therefore, the remaining life for defects 1 was about 37.83 years.

However, the remaining life for defect 1 was not representing the whole pipeline remaining life. Therefore, the average of remaining life from all defects has been taken as the pipeline remaining life. The average P-F interval period was about 76.6 years. The pipeline has been operated 32 years since its installation years, in 1977; thus, the remaining life for the pipeline was about 44.6 years.

Based on ASME B31.G method, the remaining pipeline life was 35 years. Therefore, if compared with remaining life from P-F interval period, the different percentage was about 10.6 years. Therefore, ASME B31.G showed more conservative result compared P-F interval method. However, the result from P-F interval was not confident enough because the analysis has been made only from 3 defects point. It was not represent enough the actual condition inside the pipeline. In-fact, based on the intelligent pigging (IP) data, there were several defects point which recorded on inspection in year 1997, but the same defects was not recorded on next inspection.

Thus, to improve the P-F interval model result, more defects point need to be include in the P-F interval analysis.

4.2 Degradation Analysis Result

The degradation analysis was performed on each defects point that recorded by the inspection during year 1993, year 1999, and year 2003. Based on the Eq.(7), the degradation rate or the corrosion rate for each defect has been calculated. There were about 121 of defects point recorded by intelligent pigging (IP) inspection. The details of several defects information were clearly shown in Table 4.

Table 4 : The detail of several defects recorded by IP inspection

Defect point	**absolute distance, m**	**Wall thickness, mm**				**Degradation rate, mm/year**
		Year 1977 (installation year)	**Year 1993**	**Year 1997**	**year 2009**	
1	49908.91	12.70	NA	11.176	NA	0.0725
2	53243.47	12.70	NA	10.668	NA	0.0967
3	832.50	12.70	NA	NA	11.303	0.04273623
4	1127.95	12.70	NA	NA	11.43	0.03885112
5	22680	12.70	NA	NA	11.303	0.04273623
6	834.202	12.7	NA	NA	8.509	0.1282087
7	621.62	12.7	NA	NA	4.445	0.25253229

In order to perform life data analysis, the time to failure for each defect was required. In this study, the failure has been defined as the defects have reach 80% of wall loss [11]. Thus, the linear degradation model has been used to calculate required time for each defect to reach 80% of wall loss. The highest degradation rate, 0.252 mm/year has been used to calculate the time to failure for each defects which standard practiced by pipeline operators. The Eq.(7) was used to calculate the time to failure for each defect. The details of time to failure for each defects was shown in the Table 5.

$$x = \frac{y-b}{a} \tag{7}$$

where $y = current\ wall\ thickness$

$x = time\ to\ failure$

$a = degradation\ rate$

$b = actual\ current\ wall\ thickness$

Table 5 : The time to failure for several defects

Defect point	Absolute distance, m	Wall thickness ,mm				Time to failure, years
		Year 1977 (installation year)	Year 1993	Year 1997	year 2009	
1	49908.91	12.7	NA	11.176	NA	84.09
2	53243.47	12.7	NA	10.668	NA	119.13
3	832.50	12.7	NA	NA	11.303	490.33
4	1127.95	12.7	NA	NA	11.43	228.82
5	22680	12.7	NA	NA	11.303	294.20
6	834.202	12.7	NA	NA	8.509	46.56
7	621.62	12.7	NA	NA	4.445	7.54

Next, the time-to-failure data for all defects point has been used in life data analysis using Weibull ++ software. The details of all time-to-failure data were available in the Appendices. In Weibull ++, the time-to-failure data has been fit to several type of distribution. The details of the distribution were shown in the Table 6.

Table 6 : The result of degradation analysis

Distribution type	Parameter	Log-likelihood value	Failure rate on next inspection (2015) / year	Mean life, year	Pipeline remaining life from ASME B31.G, year	Different between ASME B31.G and degradation analysis, year
Gumbel	**Mu = 283659.84h**	**-2244.245**	**2.2678**	**30.88**	**35**	**4.12**
	Sigma= 22792.32 h					
Gamma	**Mu= 8.07h**	**-1252.07**	**0.961**	**30.835**	**35**	**4.165**
	K=80.0098h					
Normal	**Median = 270115.47h**	**-1250.09**	**0.9695**	**30.835**	**35**	**4.165**
	Std= 288821.014 h					
2P-Weibull	**Beta= 11.852h**	**-1244.814**	**0.9938**	**30.9**	**35**	**4.1**
	Eta = 282600.8h					

Based on the Table 6, the time to failure data has been fitted to several distribution types. The difference distribution gives difference log-like hood value which 2-P Weibull distribution has given the highest log-like hood value compared to other distribution. Therefore, the mean life from 2-P Weibull distribution was taken as pipeline remaining life. The next inspection of the pipeline was in year 2015. Based on the selected distribution, the failure rate of the pipeline on next inspection was 0.9938 per year. The details of failure rate can be observed in the Figure 10.

However, in term of mean life, there was not much different between 2-P Weibull distributions with other distribution. In this study, the aim of the analysis was to get the mean life for the pipeline. Based on Table 6, the mean life among all distribution did not have much difference. Therefore, mean life from any distribution can be used in order to compare mean life generated from ASME B31.G.

The mean life from 2-P Weibull distribution was 30.9 years. The mean life was shorter than mean life from ASME B31.G which was 35 years. The mean life different between two method was about 4.12 years. Therefore, the degradation analysis was more conservative than ASME B31.G method. Since the mean life from degradation analysis was not much different from ASME B31.G method, degradation analysis can be used in determining the reliability of offshore pipeline.

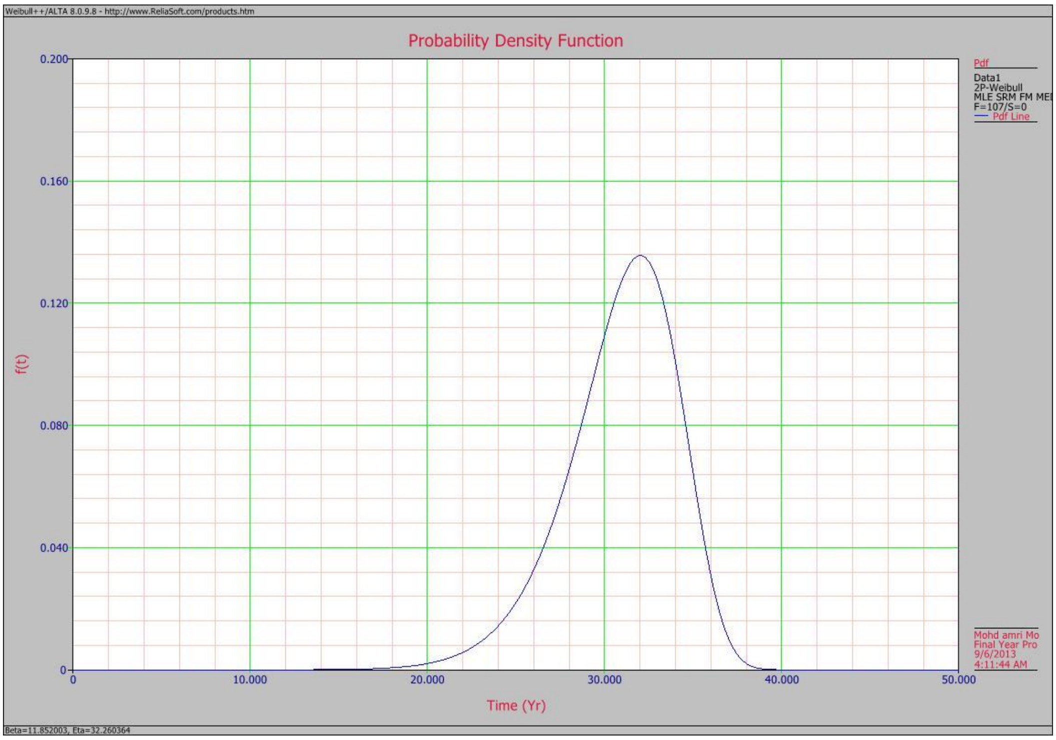

Figure 9 : The graph of probability density function 2-P Weibull distribution

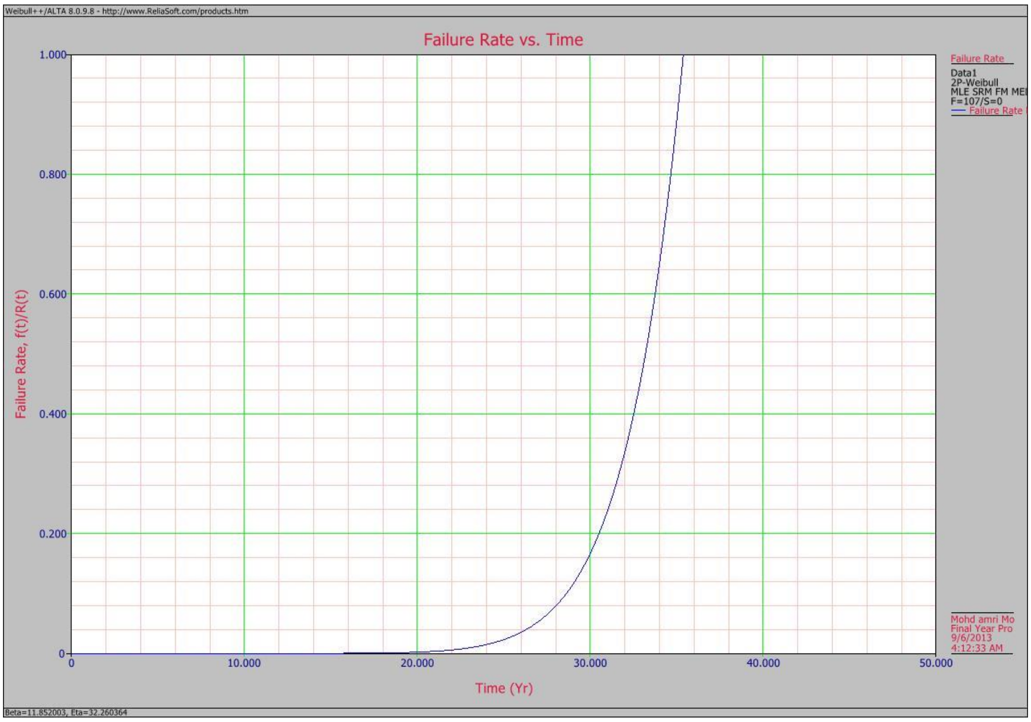

Figure 10 : The graph of failure rate 2-P Weibull distribution

Both method, P-F interval and degradation analysis were able to determine mean life of the offshore pipeline by using intelligent pigging(IP) data. Although there was some different of mean life generated by both method which was compared with ASME B31.G, the difference was small. This defferent was occured due to several reason. First was because the data limitation in P-F interval model. Only 3 defects point were consired in the analysis. Therefore, in order in get accurate result, the P-F interval required more defect information so that the result would represent the current condition of the pipeline.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

In conclusion, the objective of the study has been achieved. The pipeline remaining life can be determined using P-F interval model and degradation analysis model. The P-F interval gave 44.6 years of remaining pipeline life with. Meanwhile, degradation analysis gave 30.88 years of pipeline remaining life. Among ASME B31.G, P-F interval and degradation analysis, degradation analysis method showed more conservative result since it gave the shortest offshore pipeline mean life.

For the future recommendation, it is recommended the study applied to several pipeline in order to validate this finding. If the result did not have much different if applied to several pipeline, the method can be used in reliability assessment for offshore pipeline application. Besides that, it is recommended to consider other type of corrosion defect such as pitting corrosion, localized corrosion and pinhole corrosion because these corrosion defects also contribute to the offshore pipeline failure. Lastly, it is recommended to include all defects along the pipeline, not only Zone 2 area because for long pipeline, most of the defects were recorded outside the Zone 2 area.

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APPENDICES

Appendix 1: The Design Data For Offshore Pipeline

	Product	Year Install	Design Life (year)	D.P (bar)	DT (°C)	Material Grade	OD (mm)	WT (mm)	ID (mm)	Lgth (km)	Min Bend Radius
Pipeline A	CRUDE	1977	25	102.1	65	5LX-52	323.9	12.7	298.8	59.8	12D 90°

Appendix 2: The Gantt Chart and Milestone for FYP 1

Gannt Chart & Milestones FYP 1																
No	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Topic								Mid - Semester Break							
2	Literature Review on several study case															
3	Selection PF-interval model & degradation model for study case															
4	Information gathering on PF-interval model & degradation model															
5	Determine P and F for case study															
6	Submission of Extended Proposal															
7	Familization on Weibull ++ sofware															
8	Proposal Defence															
9	Identify Required Assumption															
10	Data Gathering															
11	Data Review & Analysis															
12	Submission of Interim Draft Report															
13	Submission of Interim Report															

Appendix 3: The Gantt Chart and Milestone for FYP 2

Gannt Chart & Milestones FYP 2																	
No	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Construct PF-Interval model								Mid - Semester Break								
2	Construct the degradation model																
3	Submission of Progress Report																
4	Result Analysis for P-F interval model																
5	Result Analysis for degradation analysisl model																
6	Pre sedex																
7	Submission Draft Report																
8	Submission of Dissertation (soft bound)																
9	Submission of Technical Paper																
10	Oral Presentation																
11	Submission of Project Dissertation (Hard Bound)																

Appendix 4: The screenshot from FFS report

Type of defects	Defect Sizing Accuracy		Internal Defects @Zone 1, Safety Class=Normal, PoF<10-4			Internal Defects @Zone 2, Safety Class=High, PoF<10-5		
	Depth sizing accuracy at 80% conf.level in+/- fraction of t	Length sizing accuracy at 80% conf.level in+/- X mm	Year PoF exceeded	Pcorr, (bar)	KP	Year PoF exceeded	Pcorr, (bar)	KP
AXGR	+/- 15	+/- 25	2064	37.5	16.167	-	-	-
AXSL	+/- 15	+/- 25	2061	36.4	1.133	-	-	-
CIGR	+/- 15	+/- 20	2012	36.4	31.622	2033	24.7	
CISL	+/- 15	+/- 20	2034	20.5	14.048	-	-	-
GENE	+/- 10	+/- 20	2054	38.3	19.932	2044	36.2	
PITT	+/- 20	+/- 15	2037	19.1	15.042	2034	28.0	

The FFS study that conducted by pipeline operator has included all type of recorded defects in the pipeline reliability assessment. However, this study only focus on generalize corrosion. Thus, the remaining life from generalize corrosion defect from FFS study has been taken for the comparison purpose.

Appendix 5: The IP inspection data with time to failure

Abs. Distance, m.	Wall Thickness, mm	Joint Length, m	Axial Length, mm	Width, mm	Depth, %	Circumferential Orientation, o'clock	Time To Failure Based highest CR (TTF) ,year
112.71	12.70	4.317	18	45	15	06:05	33.02
112.81	12.70	4.317	16	37	14	06:08	33.528
116.19	12.70	6.22	32	120	16	06:51	32.512
117.01	12.70	6.22	37	120	17	05:21	32.004
119.07	12.70	6.22	27	112	15	06:19	33.02
119.32	12.70	6.22	20	105	14	06:40	33.528
119.68	12.70	6.22	37	135	21	06:42	29.972
120.09	12.70	6.22	35	127	22	06:40	29.464
122.74	12.70	12.815	26	112	15	06:28	33.02
133.26	12.70	12.815	27	90	17	06:33	32.004
137.80	12.70	12.785	22	82	14	06:40	33.528
148.38	12.70	12.829	16	82	16	06:08	32.512
237.63	12.70	12.843	26	180	16	06:21	32.512
249.02	12.70	12.848	29	120	14	06:14	33.528
250.52	12.70	12.848	25	157	25	07:12	27.94
252.35	12.70	12.767	32	142	15	07:08	33.02
254.65	12.70	12.767	35	165	14	06:26	33.528
255.04	12.70	12.767	27	180	18	06:26	31.496
257.75	12.70	12.767	43	135	27	07:08	26.924
260.36	12.70	12.767	26	157	16	06:19	32.512
260.81	12.70	12.767	40	157	18	07:05	31.496
260.91	12.70	12.767	22	127	17	06:15	32.004
262.45	12.70	12.767	40	172	14	06:28	33.528
263.27	12.70	12.767	19	209	14	06:21	33.528
263.65	12.70	12.84	18	127	14	06:24	33.528
264.11	12.70	12.84	25	105	19	06:24	30.988
268.00	12.70	12.84	24	120	23	06:19	28.956
420.68	12.70	12.81	19	112	14	06:19	33.528
464.46	12.70	12.863	23	112	15	06:12	33.02
467.58	12.70	12.863	28	120	16	07:33	32.512
468.22	12.70	12.863	23	120	14	07:35	33.528
469.03	12.70	12.84	28	97	14	07:47	33.528

469.74	12.70	12.84	24	120	15	07:40	33.02
470.84	12.70	12.84	29	105	19	06:10	30.988
471.68	12.70	12.84	29	127	19	06:12	30.988
472.23	12.70	12.84	26	127	14	05:28	33.528
473.27	12.70	12.84	35	165	23	07:00	28.956
474.25	12.70	12.84	27	165	29	05:40	25.908
474.41	12.70	12.84	28	135	18	06:17	31.496
474.62	12.70	12.84	36	165	19	06:24	30.988
474.77	12.70	12.84	35	142	15	06:12	33.02
475.22	12.70	12.84	42	209	21	06:17	29.972
475.62	12.70	12.84	24	135	29	06:14	25.908
476.15	12.70	12.84	51	217	24	06:14	28.448
476.82	12.70	12.84	27	120	19	07:26	30.988
477.03	12.70	12.84	36	165	16	06:17	32.512
477.70	12.70	12.84	29	142	20	06:17	30.48
478.09	12.70	12.84	38	157	28	06:17	26.416
478.42	12.70	12.84	41	150	24	07:00	28.448
478.99	12.70	12.84	40	209	29	06:56	25.908
479.38	12.70	12.84	40	165	29	06:56	25.908
479.53	12.70	12.84	35	157	21	06:56	29.972
479.75	12.70	12.84	33	150	16	07:00	32.512
479.97	12.70	12.84	24	142	17	06:17	32.004
480.08	12.70	12.84	37	157	21	06:14	29.972
481.78	12.70	12.646	33	150	25	07:00	27.94
481.85	12.70	12.646	36	157	22	06:17	29.464
482.38	12.70	12.646	33	195	30	06:21	25.4
483.53	12.70	12.646	45	180	20	06:58	30.48
483.82	12.70	12.646	29	120	16	06:47	32.512
484.09	12.70	12.646	36	172	26	07:00	27.432
484.32	12.70	12.646	58	180	20	07:03	30.48
484.45	12.70	12.646	38	165	18	06:15	31.496
484.67	12.70	12.646	37	165	22	06:21	29.464
485.11	12.70	12.646	30	150	22	06:21	29.464
485.24	12.70	12.646	38	180	28	06:24	26.416
486.24	12.70	12.646	43	180	26	06:12	27.432
486.77	12.70	12.646	45	180	15	06:19	33.02
487.02	12.70	12.646	26	112	15	06:19	33.02
487.32	12.70	12.646	36	165	19	06:17	30.988
488.26	12.70	12.646	37	172	24	06:21	28.448
488.78	12.70	12.646	39	172	21	06:26	29.972
488.93	12.70	12.646	36	142	27	06:19	26.924
489.51	12.70	12.646	30	135	14	06:21	33.528
490.24	12.70	12.646	45	195	26	06:26	27.432
490.74	12.70	12.646	53	209	22	06:35	29.464
491.16	12.70	12.646	30	142	23	06:28	28.956

491.29	12.70	12.646	32	157	20	06:38	30.48
491.52	12.70	12.646	52	165	23	06:21	28.956
492.16	12.70	12.646	34	157	23	06:24	28.956
492.36	12.70	12.646	23	127	16	06:28	32.512
492.59	12.70	12.646	31	142	17	06:24	32.004
493.06	12.70	12.646	16	60	16	08:09	32.512
493.24	12.70	12.646	41	157	31	06:17	24.892
493.50	12.70	12.646	41	165	30	06:17	25.4
494.40	12.70	12.846	31	82	14	08:07	33.528
495.97	12.70	12.846	46	180	32	06:21	24.384
496.96	12.70	12.846	25	142	19	06:30	30.988
497.20	12.70	12.846	37	165	35	06:17	22.86
498.17	12.70	12.846	42	127	16	07:01	32.512
498.65	12.70	12.846	64	187	14	06:19	33.528
499.22	12.70	12.846	43	172	20	06:49	30.48
499.55	12.70	12.846	23	105	16	06:17	32.512
500.92	12.70	12.846	37	150	28	06:26	26.416
501.46	12.70	12.846	24	130	39	06:24	20.828
502.33	12.70	12.846	35	135	14	06:26	33.528
502.61	12.70	12.846	26	90	14	06:15	33.528
503.65	12.70	12.846	29	157	19	06:24	30.988
504.52	12.70	12.846	31	165	20	06:28	30.48
505.43	12.70	12.846	41	142	15	06:21	33.02
505.78	12.70	12.846	22	127	22	06:38	29.464
506.65	12.70	12.818	29	165	27	06:24	26.924
508.46	12.70	12.818	27	97	18	06:17	31.496
509.26	12.70	12.818	49	135	14	07:10	33.528
510.85	12.70	12.818	27	135	21	06:28	29.972
511.28	12.70	12.818	23	105	20	06:19	30.48
512.08	12.70	12.818	20	97	14	07:05	33.528
512.37	12.70	12.818	23	90	14	06:26	33.528
513.58	12.70	12.818	25	112	17	06:24	32.004
514.75	12.70	12.818	24	105	16	06:42	32.512
515.13	12.70	12.818	28	135	21	06:26	29.972
515.24	12.70	12.818	29	97	16	06:17	32.512
517.70	12.70	12.818	26	120	16	06:46	32.512
519.36	12.70	12.818	27	142	14	06:17	33.528
561.67	12.70	12.841	30	97	14	07:30	33.528
562.16	12.70	12.841	36	187	14	07:01	33.528
563.11	12.70	12.841	26	120	19	06:24	30.988
563.56	12.70	12.841	34	142	14	05:54	33.528
563.70	12.70	12.841	24	97	14	05:44	33.528
563.76	12.70	12.841	22	142	17	06:21	32.004
563.84	12.70	12.841	28	97	16	05:42	32.512
564.01	12.70	12.841	24	75	16	05:58	32.512

564.22	12.70	12.841	31	142	16	06:17	32.512
564.33	12.70	12.841	22	67	16	06:21	32.512
564.49	12.70	12.841	24	112	14	07:03	33.528
564.66	12.70	12.841	22	82	17	05:51	32.004
565.74	12.70	12.841	38	165	20	07:01	30.48
565.93	12.70	12.841	22	120	20	07:03	30.48
566.08	12.70	12.841	31	82	17	05:30	32.004
566.14	12.70	12.841	36	90	15	07:12	33.02
566.35	12.70	12.841	25	150	28	07:03	26.416
566.49	12.70	12.841	24	82	15	07:15	33.02
567.02	12.70	12.841	48	232	20	06:40	30.48
567.10	12.70	12.841	28	172	17	06:17	32.004
567.71	12.70	12.841	24	120	20	06:31	30.48
567.99	12.70	12.841	30	187	30	07:10	25.4
568.41	12.70	12.841	40	239	18	07:10	31.496
568.76	12.70	12.841	22	82	18	05:38	31.496
568.80	12.70	12.841	22	97	17	07:05	32.004
569.02	12.70	12.841	25	172	21	05:44	29.972
569.68	12.70	12.841	28	180	15	07:12	33.02
570.02	12.70	12.841	38	157	25	07:10	27.94
570.20	12.70	12.841	18	90	14	06:19	33.528
571.01	12.70	12.783	20	82	15	07:10	33.02
571.17	12.70	12.783	26	82	15	06:24	33.02
571.49	12.70	12.783	33	135	23	06:24	28.956
571.75	12.70	12.783	18	97	16	05:35	32.512
571.87	12.70	12.783	22	82	16	07:47	32.512
572.03	12.70	12.783	19	82	16	05:42	32.512
572.15	12.70	12.783	23	165	31	07:15	24.892
572.73	12.70	12.783	40	135	20	06:14	30.48
574.17	12.70	12.783	40	120	18	06:14	31.496
575.45	12.70	12.783	30	112	15	07:44	33.02
575.88	12.70	12.783	57	172	25	06:21	27.94
577.33	12.70	12.783	25	145	44	06:28	18.288
578.74	12.70	12.783	33	150	30	07:03	25.4
579.35	12.70	12.783	20	97	20	05:38	30.48
579.93	12.70	12.783	21	105	21	05:38	29.972
580.64	12.70	12.783	20	90	20	05:38	30.48
581.03	12.70	12.783	24	127	16	07:01	32.512
581.10	12.70	12.783	36	142	21	07:03	29.972
581.19	12.70	12.783	20	60	14	05:17	33.528
582.04	12.70	12.783	46	165	30	06:24	25.4
583.30	12.70	12.783	30	172	24	06:24	28.448
583.90	12.70	12.848	36	157	18	06:21	31.496
584.17	12.70	12.848	47	150	30	07:05	25.4
585.10	12.70	12.848	34	172	28	06:15	26.416

585.89	12.70	12.848	32	135	20	07:01	30.48
586.05	12.70	12.848	25	127	14	06:58	33.528
586.53	12.70	12.848	30	157	19	06:17	30.988
587.27	12.70	12.848	28	120	16	06:44	32.512
587.34	12.70	12.848	23	97	17	06:21	32.004
587.71	12.70	12.848	21	112	20	07:51	30.48
588.02	12.70	12.848	25	150	18	06:21	31.496
588.68	12.70	12.848	44	180	25	06:21	27.94
589.20	12.70	12.848	30	120	18	06:47	31.496
589.84	12.70	12.848	45	195	24	07:03	28.448
590.10	12.70	12.848	29	172	24	06:19	28.448
590.17	12.70	12.848	21	90	16	07:47	32.512
590.40	12.70	12.848	28	120	16	06:19	32.512
591.05	12.70	12.848	34	142	15	06:31	33.02
591.78	12.70	12.848	36	157	18	06:19	31.496
592.55	12.70	12.848	35	209	36	07:03	22.352
592.66	12.70	12.848	25	120	16	06:44	32.512
592.72	12.70	12.848	22	105	15	06:21	33.02
593.28	12.70	12.848	34	120	15	06:33	33.02
593.53	12.70	12.848	33	157	19	06:24	30.988
593.66	12.70	12.848	32	172	20	06:21	30.48
594.56	12.70	12.848	25	142	16	06:30	32.512
594.89	12.70	12.848	32	165	24	06:30	28.448
595.44	12.70	12.848	30	172	17	07:08	32.004
595.51	12.70	12.848	23	142	16	07:03	32.512
596.15	12.70	12.848	42	142	18	06:21	31.496
597.22	12.70	12.801	31	127	17	07:08	32.004
597.37	12.70	12.801	23	142	24	06:28	28.448
598.14	12.70	12.801	21	127	20	07:14	30.48
598.35	12.70	12.801	25	105	22	06:49	29.464
598.50	12.70	12.801	22	120	25	06:46	27.94
599.81	12.70	12.801	36	165	34	07:03	23.368
600.50	12.70	12.801	32	142	20	06:30	30.48
600.60	12.70	12.801	28	142	23	06:31	28.956
600.66	12.70	12.801	28	135	24	06:30	28.448
601.57	12.70	12.801	20	127	15	07:26	33.02
602.20	12.70	12.801	18	105	14	06:49	33.528
602.73	12.70	12.801	42	120	22	06:31	29.464
602.93	12.70	12.801	28	142	20	06:31	30.48
603.31	12.70	12.801	19	97	16	06:40	32.512
603.36	12.70	12.801	20	120	19	06:31	30.988
603.81	12.70	12.801	21	105	18	06:35	31.496
603.87	12.70	12.801	25	127	17	06:31	32.004
603.95	12.70	12.801	23	105	17	06:33	32.004
604.79	12.70	12.801	28	105	16	06:15	32.512

604.84	12.70	12.801	18	67	16	08:26	32.512
605.43	12.70	12.801	25	120	23	06:28	28.956
606.16	12.70	12.801	23	120	24	07:14	28.448
606.42	12.70	12.801	38	90	15	08:01	33.02
606.78	12.70	12.801	23	60	14	08:01	33.528
606.87	12.70	12.801	24	75	14	07:54	33.528
607.10	12.70	12.801	31	150	23	06:19	28.956
607.55	12.70	12.801	42	142	28	05:58	26.416
608.47	12.70	12.801	27	120	17	07:14	32.004
608.62	12.70	12.801	28	142	17	06:30	32.004
608.75	12.70	12.801	20	120	18	06:26	31.496
608.96	12.70	12.653	27	110	49	07:14	15.748
609.64	12.70	12.653	30	142	26	06:26	27.432
610.61	12.70	12.653	33	157	25	07:10	27.94
611.07	12.70	12.653	27	157	18	06:35	31.496
611.12	12.70	12.653	26	120	17	07:08	32.004
612.30	12.70	12.653	26	124	42	06:40	19.304
613.38	12.70	12.653	24	105	39	06:35	20.828
613.99	12.70	12.653	28	110	36	06:30	22.352
614.29	12.70	12.653	28	135	25	06:30	27.94
614.89	12.70	12.653	30	127	21	07:14	29.972
615.43	12.70	12.653	23	112	16	05:49	32.512
616.11	12.70	12.653	24	112	18	05:47	31.496
616.47	12.70	12.653	29	120	17	06:28	32.004
616.72	12.70	12.653	42	180	17	06:26	32.004
617.06	12.70	12.653	27	120	15	06:56	33.02
617.27	12.70	12.653	23	97	14	07:21	33.528
618.42	12.70	12.653	41	180	28	06:30	26.416
618.97	12.70	12.653	28	142	29	06:31	25.908
619.50	12.70	12.653	28	127	28	06:30	26.416
620.19	12.70	12.653	32	135	31	06:30	24.892
620.42	12.70	12.653	20	105	17	06:28	32.004
620.95	12.70	12.653	40	180	27	06:17	26.924
621.07	12.70	12.653	24	120	17	06:31	32.004
621.25	12.70	12.653	33	112	21	06:30	29.972
621.53	12.70	12.653	27	135	26	06:38	27.432
622.24	12.70	12.791	44	127	17	06:30	32.004
623.72	12.70	12.791	29	127	23	06:30	28.956
624.22	12.70	12.791	44	157	30	06:33	25.4
624.58	12.70	12.791	25	105	17	06:24	32.004
624.92	12.70	12.791	33	120	22	06:15	29.464
626.21	12.70	12.791	28	135	30	06:26	25.4
626.91	12.70	12.791	28	142	19	05:49	30.988
627.48	12.70	12.791	23	120	30	06:26	25.4
628.12	12.70	12.791	32	112	16	06:28	32.512

628.34	12.70	12.791	21	134	39	06:28	20.828
629.26	12.70	12.791	24	157	17	06:38	32.004
629.67	12.70	12.791	27	112	22	06:28	29.464
629.88	12.70	12.791	30	142	25	06:26	27.94
630.09	12.70	12.791	26	105	30	06:26	25.4
630.46	12.70	12.791	30	150	35	06:26	22.86
630.57	12.70	12.791	23	116	40	06:30	20.32
630.81	12.70	12.791	19	113	36	06:28	22.352
631.23	12.70	12.791	25	120	14	06:26	33.528
631.58	12.70	12.791	25	127	30	06:28	25.4
631.65	12.70	12.791	29	135	21	06:26	29.972
631.87	12.70	12.791	30	120	28	06:28	26.416
631.94	12.70	12.791	22	105	18	06:28	31.496
632.05	12.70	12.791	27	120	20	06:26	30.48
632.29	12.70	12.791	26	120	20	06:26	30.48
632.46	12.70	12.791	26	127	18	06:26	31.496
632.57	12.70	12.791	25	142	24	06:24	28.448
632.80	12.70	12.791	32	112	16	06:26	32.512
632.94	12.70	12.791	22	97	14	06:24	33.528
633.21	12.70	12.791	32	150	22	06:28	29.464
634.04	12.70	12.791	22	105	17	06:24	32.004
634.19	12.70	12.791	37	165	28	06:28	26.416
634.41	12.70	12.831	37	60	26	07:12	27.432
634.79	12.70	12.831	24	105	20	06:24	30.48
635.07	12.70	12.831	32	165	28	06:26	26.416
635.61	12.70	12.831	33	142	22	06:24	29.464
635.86	12.70	12.831	31	135	29	06:24	25.908
636.19	12.70	12.831	31	112	25	06:28	27.94
636.41	12.70	12.831	33	127	25	06:24	27.94
636.76	12.70	12.831	29	82	16	06:33	32.512
637.03	12.70	12.831	36	127	17	06:28	32.004
637.34	12.70	12.831	23	127	24	06:26	28.448
637.73	12.70	12.831	39	157	30	06:28	25.4
638.10	12.70	12.831	31	142	21	06:30	29.972
639.20	12.70	12.831	21	105	14	07:03	33.528
639.43	12.70	12.831	31	172	18	06:38	31.496
639.54	12.70	12.831	33	142	24	06:28	28.448
640.37	12.70	12.831	34	157	21	06:28	29.972
640.70	12.70	12.831	42	172	20	06:33	30.48
641.50	12.70	12.831	37	142	14	06:28	33.528
641.72	12.70	12.831	29	127	19	06:31	30.988
642.96	12.70	12.831	28	142	23	06:30	28.956
643.39	12.70	12.831	24	97	14	06:14	33.528
643.79	12.70	12.831	23	127	17	06:30	32.004
644.91	12.70	12.831	28	105	15	05:51	33.02

645.46	12.70	12.831	34	150	14	06:30	33.528
646.12	12.70	12.831	30	90	15	06:30	33.02
647.21	12.70	12.831	32	127	37	06:21	21.844
648.27	12.70	12.772	31	135	19	06:28	30.988
648.58	12.70	12.772	44	180	29	07:31	25.908
649.33	12.70	12.772	42	150	20	06:26	30.48
649.87	12.70	12.772	33	120	15	06:30	33.02
652.27	12.70	12.772	38	157	32	06:26	24.384
652.47	12.70	12.772	31	142	18	06:28	31.496
654.22	12.70	12.772	25	157	23	06:26	28.956
654.94	12.70	12.772	37	172	25	06:21	27.94
656.45	12.70	12.772	31	142	22	06:28	29.464
659.68	12.70	12.772	22	157	19	06:40	30.988
719.70	12.70	12.756	24	97	14	07:10	33.528
722.88	12.70	12.601	28	135	20	06:24	30.48
726.67	12.70	12.601	29	195	15	05:38	33.02
728.67	12.70	12.601	20	105	19	05:42	30.988
732.60	12.70	12.601	27	120	14	07:46	33.528
732.67	12.70	12.601	23	142	14	05:44	33.528
734.71	12.70	12.601	33	165	18	06:17	31.496
735.46	12.70	12.601	28	247	29	07:03	25.908
745.95	12.70	12.722	39	180	14	05:35	33.528
749.09	12.70	12.821	22	105	15	06:40	33.02
760.08	12.70	12.821	32	142	17	07:08	32.004
761.35	12.70	12.808	30	120	14	06:26	33.528
761.58	12.70	12.808	32	112	15	06:19	33.02
762.71	12.70	12.808	25	120	18	07:08	31.496
763.11	12.70	12.808	23	97	19	06:42	30.988
763.99	12.70	12.808	22	157	20	06:26	30.48
764.29	12.70	12.808	27	120	15	06:21	33.02
766.97	12.70	12.808	45	150	15	07:05	33.02
767.30	12.70	12.808	36	142	24	06:30	28.448
767.61	12.70	12.808	28	135	23	06:28	28.956
767.75	12.70	12.808	28	150	16	07:05	32.512
768.14	12.70	12.808	33	135	17	06:15	32.004
768.31	12.70	12.808	41	142	26	06:24	27.432
768.61	12.70	12.808	32	172	22	06:21	29.464
768.90	12.70	12.808	22	105	19	06:19	30.988
769.02	12.70	12.808	45	150	22	06:26	29.464
769.16	12.70	12.808	25	97	14	06:21	33.528
769.49	12.70	12.808	28	127	20	06:19	30.48
769.73	12.70	12.808	39	157	16	06:58	32.512
770.21	12.70	12.808	30	112	31	06:19	24.892
770.23	12.70	12.808	22	60	16	07:14	32.512
770.42	12.70	12.808	30	142	20	06:17	30.48

770.54	12.70	12.808	29	135	19	06:28	30.988
771.16	12.70	12.808	33	209	18	06:28	31.496
771.69	12.70	12.808	27	120	22	06:26	29.464
772.68	12.70	12.808	26	97	14	06:21	33.528
773.09	12.70	12.808	39	127	16	06:19	32.512
773.16	12.70	12.808	26	142	20	06:26	30.48
774.62	12.70	12.844	20	142	17	06:17	32.004
775.33	12.70	12.844	28	142	24	06:30	28.448
775.42	12.70	12.844	26	150	14	05:54	33.528
775.72	12.70	12.844	26	105	14	06:10	33.528
775.86	12.70	12.844	42	127	14	06:21	33.528
776.39	12.70	12.844	23	112	17	05:35	32.004
776.59	12.70	12.844	35	157	14	06:19	33.528
777.55	12.70	12.844	44	135	24	06:24	28.448
777.73	12.70	12.844	29	127	15	06:21	33.02
778.27	12.70	12.844	32	157	18	06:21	31.496
778.99	12.70	12.844	48	165	19	07:03	30.988
780.51	12.70	12.844	28	120	14	06:21	33.528
781.16	12.70	12.844	25	112	16	07:03	32.512
781.71	12.70	12.844	35	150	28	06:28	26.416
782.33	12.70	12.844	38	150	19	06:54	30.988
783.26	12.70	12.844	32	142	21	06:21	29.972
783.36	12.70	12.844	36	142	22	06:21	29.464
784.21	12.70	12.844	34	142	18	06:26	31.496
785.86	12.70	12.844	42	165	22	06:24	29.464
787.21	12.70	12.702	50	187	21	06:26	29.972
787.36	12.70	12.702	35	150	28	07:01	26.416
788.95	12.70	12.702	48	157	14	06:17	33.528
789.11	12.70	12.702	45	165	17	06:21	32.004
789.54	12.70	12.702	36	142	15	06:26	33.02
789.98	12.70	12.702	38	150	24	06:21	28.448
791.01	12.70	12.702	47	165	14	06:19	33.528
791.26	12.70	12.702	38	165	24	07:03	28.448
792.16	12.70	12.702	38	127	17	06:19	32.004
793.68	12.70	12.702	40	172	19	06:58	30.988
793.87	12.70	12.702	33	135	20	06:15	30.48
795.16	12.70	12.702	48	150	20	06:58	30.48
796.47	12.70	12.702	48	157	22	06:19	29.464
797.90	12.70	12.702	30	135	34	06:19	23.368
798.03	12.70	12.702	28	157	21	06:21	29.972
798.69	12.70	12.702	27	134	37	06:21	21.844
799.00	12.70	12.702	34	142	32	06:19	24.384
799.30	12.70	12.702	32	112	15	06:19	33.02
800.14	12.70	12.81	26	112	14	06:21	33.528
800.39	12.70	12.81	56	172	14	07:01	33.528

800.54	12.70	12.81	39	157	26	06:21	27.432
801.13	12.70	12.81	27	157	26	06:17	27.432
801.43	12.70	12.81	23	120	15	05:49	33.02
801.57	12.70	12.81	63	157	18	06:54	31.496
801.71	12.70	12.81	25	127	19	06:17	30.988
801.90	12.70	12.81	36	150	30	06:15	25.4
802.31	12.70	12.81	37	157	23	06:15	28.956
802.40	12.70	12.81	35	127	18	06:24	31.496
802.75	12.70	12.81	23	82	15	06:19	33.02
802.81	12.70	12.81	18	97	20	06:19	30.48
803.01	12.70	12.81	33	142	34	06:24	23.368
803.13	12.70	12.81	31	142	28	06:17	26.416
803.57	12.70	12.81	35	142	32	06:21	24.384
804.26	12.70	12.81	49	172	24	07:01	28.448
804.87	12.70	12.81	41	157	26	06:26	27.432
805.23	12.70	12.81	53	232	26	06:17	27.432
805.67	12.70	12.81	31	150	22	06:56	29.464
806.21	12.70	12.81	31	172	29	06:49	25.908
807.39	12.70	12.81	25	127	18	06:17	31.496
807.88	12.70	12.81	56	180	17	06:58	32.004
808.59	12.70	12.81	40	165	25	06:01	27.94
809.68	12.70	12.81	23	97	16	06:17	32.512
809.88	12.70	12.81	38	172	26	06:17	27.432
811.99	12.70	12.81	25	157	15	06:15	33.02
812.13	12.70	12.81	35	135	27	06:21	26.924
812.17	12.70	12.708	20	67	16	04:26	32.512
812.69	12.70	12.708	17	82	14	06:14	33.528
813.19	12.70	12.708	35	157	21	06:28	29.972
814.74	12.70	12.708	20	82	23	05:47	28.956
815.12	12.70	12.708	23	82	17	06:12	32.004
815.89	12.70	12.708	28	120	14	06:40	33.528
816.24	12.70	12.708	35	135	17	07:01	32.004
816.68	12.70	12.708	29	127	26	06:17	27.432
816.90	12.70	12.708	34	127	15	06:10	33.02
817.19	12.70	12.708	27	112	15	06:15	33.02
817.61	12.70	12.708	33	172	19	06:12	30.988
817.98	12.70	12.708	43	180	14	06:24	33.528
818.62	12.70	12.708	31	120	19	06:58	30.988
819.95	12.70	12.708	45	142	18	06:21	31.496
823.53	12.70	12.708	24	82	14	06:05	33.528
825.61	12.70	12.756	31	187	14	06:44	33.528
826.56	12.70	12.756	18	127	15	06:12	33.02
829.07	12.70	12.756	27	180	14	06:08	33.528
829.85	12.70	12.756	29	165	21	06:19	29.972
834.46	12.70	12.756	27	120	17	06:54	32.004

834.99	12.70	12.756	44	112	29	06:35	25.908
836.13	12.70	12.756	24	112	14	07:33	33.528
837.55	12.70	12.756	32	157	14	06:05	33.528
839.64	12.70	12.795	36	142	20	06:21	30.48
848.08	12.70	12.795	29	135	14	06:05	33.528
940.52	12.70	12.165	28	105	14	06:05	33.528
941.60	12.70	12.165	26	90	16	06:00	32.512
941.83	12.70	12.165	30	90	15	06:58	33.02
942.02	12.70	12.165	22	120	37	06:49	21.844
942.75	12.70	12.165	25	142	14	06:05	33.528
943.94	12.70	12.165	60	180	22	06:47	29.464
944.61	12.70	12.165	32	142	19	06:47	30.988
945.27	12.70	12.165	37	142	16	06:47	32.512
945.50	12.70	12.165	27	172	20	06:46	30.48
946.07	12.70	12.165	26	157	16	06:33	32.512
946.15	12.70	12.165	33	127	16	06:40	32.512
946.77	12.70	12.165	31	120	22	06:49	29.464
947.09	12.70	12.165	27	127	15	06:46	33.02
948.62	12.70	12.165	36	135	15	06:46	33.02
949.34	12.70	12.165	30	150	21	06:05	29.972
950.00	12.70	12.165	25	105	14	06:49	33.528
951.18	12.70	12.165	29	120	24	06:49	28.448
951.22	12.70	12.165	16	105	18	06:47	31.496
951.65	12.70	12.165	25	120	19	06:54	30.988
952.71	12.70	12.818	22	142	26	06:05	27.432
953.19	12.70	12.818	37	150	18	06:46	31.496
955.11	12.70	12.818	20	127	17	06:49	32.004
956.01	12.70	12.818	27	165	18	06:47	31.496
957.95	12.70	12.818	18	135	15	06:33	33.02
958.06	12.70	12.818	34	150	21	06:47	29.972
977.73	12.70	12.827	15	90	19	06:03	30.988
982.99	12.70	12.827	22	112	14	06:49	33.528
990.54	12.70	12.691	23	135	29	06:05	25.908
1131.32	12.70	12.76	15	82	14	06:44	33.528
1131.51	12.70	12.76	29	127	15	06:03	33.02
1133.27	12.70	12.76	31	105	20	06:46	30.48
1134.21	12.70	12.76	26	105	14	06:15	33.528
1137.07	12.70	12.76	21	97	22	06:44	29.464
1137.43	12.70	12.76	30	142	15	06:51	33.02
1138.24	12.70	12.76	28	142	14	06:46	33.528
1139.27	12.70	12.76	26	112	16	06:42	32.512
1139.71	12.70	12.76	27	127	16	06:47	32.512
1139.77	12.70	12.76	20	82	14	06:00	33.528
1142.97	12.70	12.76	16	127	17	06:44	32.004
1143.14	12.70	12.76	26	120	16	06:47	32.512

1144.46	12.70	12.847	19	120	17	06:49	32.004
1149.60	12.70	12.847	27	105	15	06:01	33.02
1180.48	12.70	12.791	35	157	16	06:38	32.512
1180.89	12.70	12.791	26	112	16	06:38	32.512
1182.95	12.70	11.716	20	120	16	06:35	32.512
1184.60	12.70	11.716	18	127	21	06:38	29.972
1187.96	12.70	11.716	28	112	14	06:42	33.528
1188.75	12.70	11.716	30	120	15	06:44	33.02
1190.39	12.70	11.716	26	127	20	06:40	30.48
1191.81	12.70	11.716	35	142	24	06:28	28.448
1192.12	12.70	11.716	18	120	21	06:42	29.972
1193.87	12.70	11.716	34	75	19	07:10	30.988
1308.95	12.70	12.372	31	97	30	06:26	25.4
1380.91	12.70	12.838	19	120	15	06:35	33.02
1507.36	12.70	12.763	22	105	14	06:46	33.528
1553.94	12.70	12.842	16	82	14	06:44	33.528
1557.07	12.70	12.842	34	120	14	06:40	33.528
1603.60	12.70	12.785	19	97	14	06:40	33.528
1609.74	12.70	12.785	27	120	14	06:38	33.528
1816.43	12.70	12.84	14	97	15	06:42	33.02
2035.57	12.70	12.822	22	75	14	06:08	33.528

Appendix 6: The input data for P-F Interval Model

Defect points	Absolute Distance, m	Inspection 1993		Inspection 1997		Inspection 2009	
		Operating period, year	Wall loss percentage, %	Operating period, year	Wall loss percentage, %	Operating period, year	Wall loss percentage, %
1	4720.70	16.52	15.00	21.02	18.00	32.69	27.00
2	5409.90	16.52	15.00	21.02	23.00	32.69	29.00
3	41363.04	16.52	15.00	21.02	18.00	32.69	33.00