CERTIFICATION OF APPROVAL

CORROSION PREDICTION MODEL OF CORRODED PIPELINE USING GUMBEL

by

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Approved by,

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CERTIFICATION OF ORIGINALITY

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

YAP PUN CHEE

ABSTRACT

Corrosion is an important degradation mechanism that can affect the reliability and integrity of the pipeline. Offshore pipelines are usually inspected using MFL Intelligent Pigging method; this is how internal pipeline corrosion can be definitively measured. However, a huge amount of thickness profile data was not used optimally to predict the corrosion rate. A reliable corrosion rate model is paramount to determine the re-inspection time interval and corrosion mitigation for pipelines. The objective of this final year project is to predict and analyze the internal pipeline corrosion for the chosen case study and develop a corrosion model. The methodology used in this project includes data gathering, data review, classification into defect type, data analysis, corrosion modelling, validation and discussion. The IP data was modelled with Gumbel distribution and result show that the data fits the curve and predicted the time to failure was for another 60 years. The result from Gumbel was compared to the deterministic approach of average time to failure of 149 years. The percent error was 40%. The project met the objective and can be further developed.

ACKNOWLEDGEMENTS

I would like to express my gratitude to AP Ir Dr Mokhtar Che Ismail who inspired, guided and helped me throughout the year. I would also like to acknowledge Ir Dr Idris Ibrahim and Dr Bambang Ari Wahjoedi for their kind advice and constructive criticism. Last but not least, I would like to express my appreciation to my friends and family for the support and love they showed through this busy period.

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ABBREVIATION

PCSB	PETRONAS Carigali Sdn Bhd
PCSB-PMO	PETRONAS Carigali Sdn Bhd – Peninsula Malaysia Operation
CPIMS	Carigali Pipeline Integrity Management System
KE-A	Kepong A
TI-A	Tiong A
MFL	Magnetic Flux Leakage
MIC	Microbial Induced Corrosion
SRB	Sulphide Reducing Bacteria
IP	Intelligent Pigging
ASME	American Society of Mechanical Engineers
MAOP	Maximum Allowable Operating Pressure
PITT	Pitting
GENE	General
INT	Internal
PINH	Pinhole
AXGR	Axial Grooving
AXSL	Axial Slotting
CIGR	Circumferential Grooving
CISL	Circumferential Slotting
H2S	Hydrogen Sulphide
KP	Kilometer Post
LD	Log Distance

CHAPTER 1

INTRODUCTION

1.1 Background Study

In a study conducted by C.C. Technologies Inc. [1], Federal Highway Agencies (FHWA) [2] and National Association of Corrosion Engineers [3]; the cost was estimated to be 276 billion US dollars. In a previous study conducted in 1975 by Battelle Columbus Laboratories, Columbus, USA and National Institute of Standards and Technology (NIST), the cost was estimated to be 82 billion US dollars, which would have mean 350 billion US dollars due to inflation over the years.

Without best practices corrosion prevention strategy, corrosion will continue and the cost of repairing a deteriorating pipeline will continue to escalate. Developing an optimum approach that includes both inspection and corrosion prevention strategies is critical to the future safety and the cost-effective operation of transmission pipelines. Realizing that corrosion prevention will never be 100% effective, an inspection strategy “find it and fix it”, in addition to the corrosion prevention strategy is required for those pipelines that have a higher probability of corrosion. A Pipeline Inspection Gauge or simply “PIG” refers to a sophisticated electronics connected to calipers which monitor the inside diameter of the pipe. Surface pitting and corrosion, as well as cracks and weld defects in steel/ferrous pipelines are often detected using Magnetic Flux Leakage (MFL) pigs. Pigging is important for cleaning, inspection and gauging especially for corrosion mitigation.

Significant savings are possible by optimizing the inspection and corrosion prevention strategies. In order to achieve such optimization, a reliable corrosion rate model is paramount to determine a re-inspection time interval for pipelines.

PMOPL24 is a 10” diameter pipeline with 6.9km length carrying wet and semi processed crude oil from KE-A platform to TI-A platform. It was built in 1982 and had a design life of 20 years. The original design life expired in 2002 and now it has been in operation for 25 years. The reported Maximum Allowable Operating Pressure (MAOP) is 40 bars which is de-rated pressure from 93 bars based on the Fitness for Service (FFS) Assessment by PRSS/DNV in 2005. The pipeline is currently operating at average Operating Pressure (OP) of 28 bars. PCSB, PMO has requested PETRONAS Group Technology Solutions (PGTS) to perform FFS assessment to determine the pipeline integrity for this pipeline.

An inline inspection using Magnetic Flux Leakage (MFL) tool was conducted by Romstar in November 2006. The IP reported to 10,804 metal loss defects with 10,803 internal defects concentrated at 700m from KE-A platform. There is only 1 external defect reported at KE-A riser.

For projected integrity, it is found that this pipeline had already exceeded the corroded pipeline pressure against MAOP at the year of inspection, 2006.

1.2 Problem Statement

As discussed, the case study for this project PMOPL24 that is located in Terengganu is found that the pipeline had already exceeded the design life and is operating under integrity status. From the latest inspection by Romstar (2006), the inspection reported 10896 defects with 10804 defects due to metal loss. Out of this number, 10803 defects are internal defects which concentrated at 700m from KE-A platform and only 1 external defect reported.

Because it is already operating under pressure, it is important for us to know the intervals of re-inspection and estimate the probability of time to failure. Therefore, a reliable corrosion rate model is needed.

1.2.1 Significance of project

Because it is almost impossible to prevent corrosion, it is becoming more apparent that controlling the corrosion rate may be the most economical solution. Engineers are therefore increasingly involved in estimating the cost of their solutions to estimating the useful life of equipment.

1.3 Objective & Scope of Study

The objective of this corrosion assessment is to determine appropriate corrosion rate to be used to:

- Develop a corrosion simulated test cell based on case study, Peninsular Malaysia Operation (PMO)
- Project the future growth of any metal loss defect due to corrosion

Scope of study:

- Internal Corrosion Modeling
- CO_2 Corrosion
- Pitting corrosion
- Background study on PMO

1.4 Relevancy of the Project

This project is relevant to the case study as statistics have shown that most of the age of the pipelines has already exceeded the design life. Many more in other operations are operating under integrity status as well; therefore an alternative corrosion prediction model can estimate the probability time of failure and help make better decisions.

1.5 Feasibility of the project

The project is believed to be feasible given that the information needed from Peninsular Malaysia Operation can be obtained on time.

CHAPTER 2

LITERATURE REVIEW & THEORY

2.1 Corrosion

Corrosion: The deterioration of a metal or its properties, attacks every component at every stage in the life of every oil and gas field. From casing strings to production platforms, from drilling through to abandonment, corrosion is an adversary worthy of all the high technology and research we can afford.

Corrosion encountered in petroleum production operations involves several mechanisms. The common types of corrosion can be summarized into Figure 1.

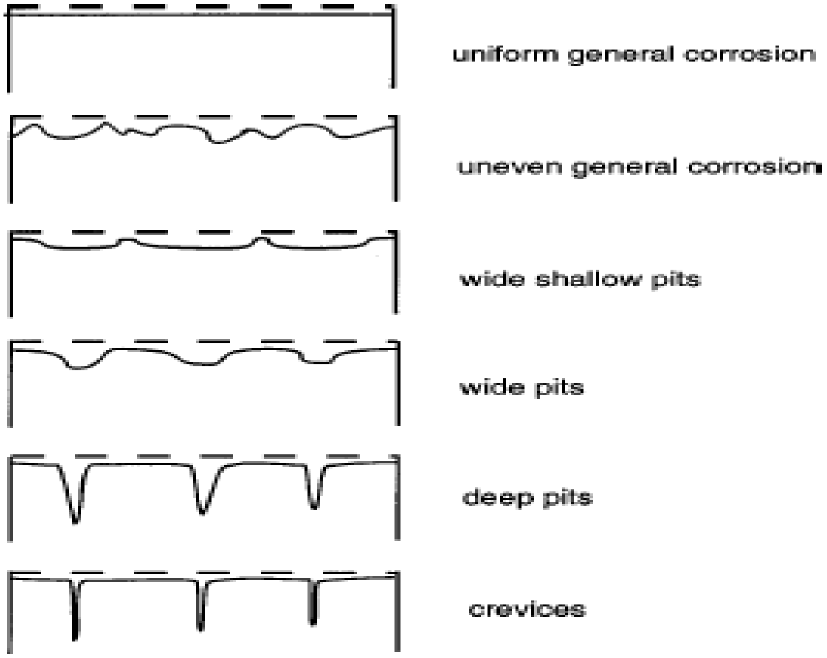


Figure 1: Corrosion types (Reference [9], Kowaka M: Introduction to life prediction of industrial plant materials)

Aging underground oil and gas pipelines can suffer from several localized forms of corrosion, primarily pitting. Often termed “under deposit corrosion”, pitting is a form of extremely localized corrosion that leads to the creation of small holes in the metal. The driving power for pitting corrosion is the lack of oxygen around a small area. This area becomes anodic while the area with excess of oxygen becomes cathodic, leading to a very localized galvanic corrosion. The corrosion penetrates the mass of metal, with limited diffusion of ions further pronouncing the localized lack of oxygen. The mechanism of pitting corrosion is probably the same as crevice corrosion.

Pitting corrosion can be considered as a combination of two physical processes: the pit generation process and its depth growth process. Both processes are uncertain and can be modeled by stochastic processes. In this project, a model that combines two stochastic processes to describe pitting corrosion is applied.

In this model, the pit generation process is represented by the Poisson process, and the pit depth growth process is modeled by Markov process. The probability distribution of corrosion pit depth and the probability time-to-failure are derived based on the combined stochastic processes.

2.2 Pitting corrosion depth

Pitting corrosion is a localized corrosion that is very destructive because a perforation resulting from a single pit can cause failure of an engineering system. If d(t) denotes the corrosion pit depth at time t, and h denotes the critical depth of interest for a structure, and if d(t) is larger than h, the performance of the structure is not satisfactory and failure occurs. The probability of d(t) larger than h equals the probability of failure. In particular, if h is set equal to a pipe wall thickness or a plate thickness, perforation of a pipe or the plate occurs when $d(t) > h$. The probability of failure in a time interval t_0 to t (or probability of time to failure) is equal to the probability of $d(t) > h$, given that $d(t_0)$ is $< h$. Therefore, it is important to provide a probabilistic method for the analysis of pit depth as a function of time.[4]

Assuming that $\{X(t), t \geq 0\}$, $X(t) \in [0,\ldots,n]$ denote the discretized states of the pit depth at time t, time t does not necessarily represent the actual exposure time. Rather, it represents a non-linear function of the actual exposure time. The state (n) is used to represent the state of failure. Given an initial probability mass function (pmf) of the pit depth, the pmf at a future time (t) can be obtained using the probability transition functions. If X(t) Є [0,…,n] is assumed to be a homogenous Markov process, the transition probability function from the damage state i to the damage state j in a time increment τ, $p_{ij}(\tau)$, i, j Є [1,n], satisfies the forward Kolmogorov differential equation:

$$\frac{\partial P(\tau)}{\partial \tau} = P(\tau)A \qquad (1)$$

Where P(τ) is a matrix of n x n with the elements defined by $p_{ij}(\tau)$, and A is a constant matrix of n x n with the elements a_{ij} representing the intensities of the transition. If the intensities of transition a_{ij} are given by:

$$\begin{aligned} a_{ii} &= -\lambda,\ 1 \le i < n \\ a_{ii+1} &= \lambda,\ 1 \le i < n \\ a_{ij} &= 0,\ \text{otherwise} \qquad (2) \end{aligned}$$

where λ is a constant to be determined, the solution of Equation (1) is:

$$P(\tau) = \begin{bmatrix} e^{-\lambda\tau} & (\lambda\tau)e^{-\lambda\tau} & (\lambda\tau)^2 e^{-\lambda\tau}/2! & \cdots & (\lambda\tau)^{n-2}e^{-\lambda\tau}/(n-2)! & 1 - e^{-\lambda\tau}\sum_{i=1}^{n-1}\frac{(\lambda\tau)^{i-1}}{(i-1)!} \\ 0 & e^{-\lambda\tau} & (\lambda\tau)e^{-\lambda\tau} & \cdots & (\lambda\tau)^{n-3}e^{-\lambda\tau}/(n-3)! & 1 - e^{-\lambda\tau}\sum_{i=1}^{n-2}\frac{(\lambda\tau)^{i-1}}{(i-1)!} \\ 0 & 0 & e^{-\lambda\tau} & \cdots & (\lambda\tau)^{n-4}e^{-\lambda\tau}/(n-4)! & 1 - e^{-\lambda\tau}\sum_{i=1}^{n-3}\frac{(\lambda\tau)^{i-1}}{(i-1)!} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & e^{-\lambda\tau} & 1 - e^{-\lambda\tau} \\ 0 & 0 & 0 & \cdots & 0 & 1 \end{bmatrix} \qquad (3)$$

This equation indicates the transition probability function $P(\tau)$ depends directly upon the normalized time increment $(\lambda\tau)$. If a corrosion pit is generated at time t_0 with depth in the first damage state (or a corrosion pit starts to grow at time t_0 with initial damage in State 1), the pmf at time t is given by:

$$\Gamma(t) = [1, 0,\ldots,0]\ P(\tau) = [p_{11}(\tau), p_{12}(\tau),\ldots p_{In}(\tau)] \qquad (4)$$

Where $\tau = t - t_0$.

Given the initial damage that is in State 1, the cumulative distribution function of the damage states $F(i, \tau)$ after a time increment τ (i.e., the probability of the damage states less than or equal to State i after a time increment $[\tau]$) can be calculated using:

$$F(i,\tau) = \sum_{k=1}^{1} P1, k(\tau), \text{ where } i = 1,.., n \qquad (5)$$

2.3 Pit Generation and Combined Effect

A simple model considers that pit generation is a homogenous Poisson process.[5] The use of the Poisson process for the pit generation has been adopted in this model. If $\{N(t), t > 0\}$ denotes the number of pits generated (starting to grow) from t_0 to t, and assuming that $\{N(t), t > 0\}$ is a homogenous Poisson process with occurrence rate v, and if a pit is generated at time u_i $(0 < u_i \leq t)$ with the depth within State 1, the pmf of the damage states occupied by the pit at time t $(\Gamma_i[t])$ can be obtained from Equation (4) resulting in:

$$\Gamma_1 (t) = [1,0,\ldots,0]\ P(\partial_1) = [p_{11}(\partial_1), p_{12}(\partial_1),\ldots,p_{In}(\partial_1)] \qquad (6)$$

Where ∂_I, $\partial_I = t - u_i$ is the time increment.

If the depths of pits are assumed to be independent and identically distributed with pmf shown in Equation (6), it can be shown that the probability that the maximum pit depth is less than or equal to State 1 (due to all the pits generated within time interval [0,t]), $\theta_i(t)$ is given by:

$$\Theta_1(t) = \exp\{ -vt[1-Pi,t)]\}, \text{ where } i = 1,\ldots,n-1 \qquad (7)$$

$$\Theta_n(t) = 1 \qquad (8)$$

$$P(i, t) = \frac{1}{\lambda\tau}\sum_{j=1}^{1}\frac{\gamma(j,\lambda t)}{(j-1)!}, \text{ where } i = 1,\ldots,n-1 \qquad (9)$$

The probability of time to failure caused by all pits generated from t_0 to t, $P_{fsys}(t)$, is equal to 1-$\theta_n(t)$:

$$P_{fsys}(t) = 1 - \exp\{-vt[1-P(n-1,t)]\} \qquad (10)$$

This equation indicates that the probability of failure is an increasing function of the occurrence rate v. P(n-1, t) represents the probability that the state corresponding to the maximum pit depth of all the pits generated within (0,t) is less than or equal to the state of failure (n). If P(n-1,t) equals zero (i.e., all the generated pits have an initial depth in the state of failure), the combined process reduces to a pure homogenous Poisson process, and the probability of failure is equal to one minus the probability of no generation of pits (e^{-vt}). The probability of failure is 0 if P(n-1,t) = 1. Further, the right side of Equation (10) can be expressed as 1-exp{-(v/λ)λt[1-P(n-1,t)]} and that P(n-1,t) depends upon the normalized time (λt). This shows that $P_{fsys}(t)$ is a function of λt and v/λ. For a given value of λt, the probability of time to failure increases as v/λ increases.

CHAPTER 3

METHODOLOGY

3.1 Flowchart

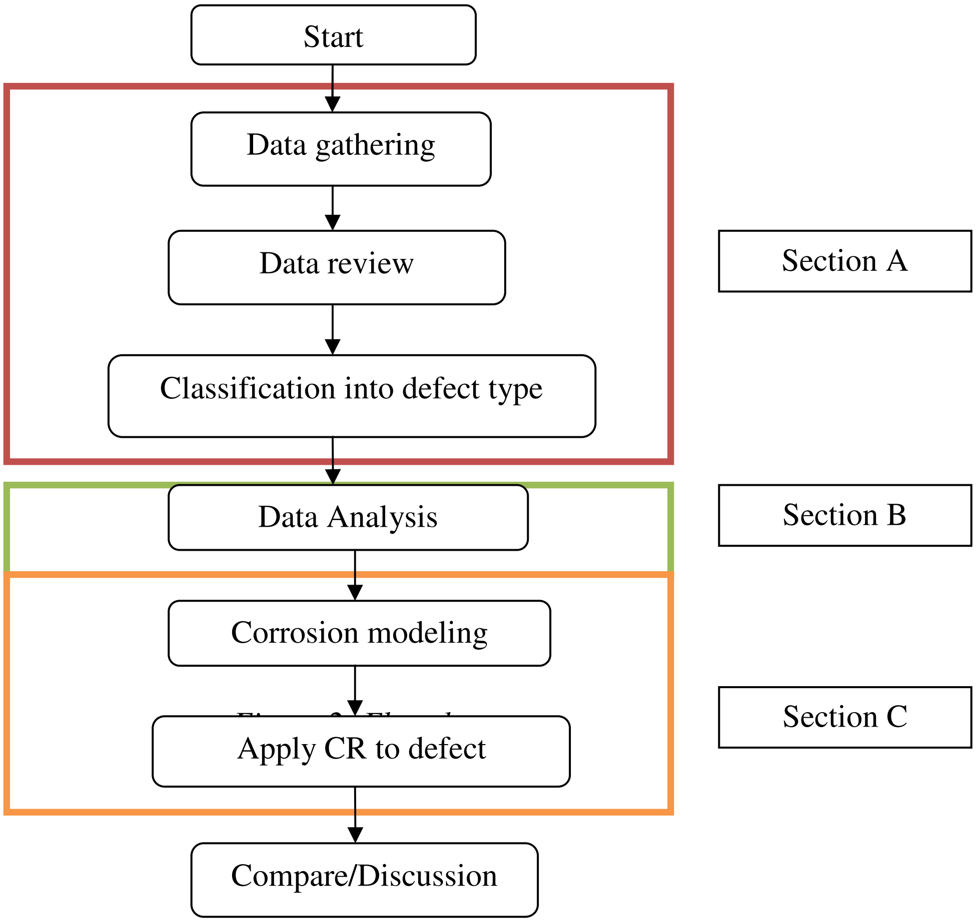


Figure 2: Flowchart

The methodology in this report will only concentrate on corrosion modelling for the case study and will be discussed further in the next chapter.

3.2 Tools

Tools needed for this project:

- WinSmith Software
- Microsoft Excel

3.3 Key Milestone: Gantt Chart

FYP1

Table 1: Gantt Chart for FYPI, II

Week Number Activities/Milestone	1	2	3	4	5	6	7	8	9	10		11	12	13	14
FYP briefing															
Project acceptance		🟨													
Project initial research and brainstorming		🟨	🟨												
Preliminary report submission				🟨											
Further research on topics				🟨	🟨	🟨	🟨	🟨	🟨	🟨		🟨	🟨	🟨	🟨
Information from PMO							🟨	🟨	🟨	🟨		🟨	🟨		
Testing								🟨	🟨	🟨		🟨	🟨	🟨	🟨
Final report										🟨		🟨	🟨	🟨	
Oral Presentation, Poster exhibition, demo/simulation													🟨		
EDX (*if any)														🟨	
Submission of Final Report															🟨

*subject to change

FYPII

Week Number Activities/Milestone	1	2	3	4	5	6	7	8	9	10		11	12	13	14
Further research on topics	■	■	■	■	■	■	■	■	■	■					
Information from PMO	■	■	■	■	■	■									
Compare data				■	■	■	■	■	■	■					
Analyze data						■	■	■	■	■		■			
Final report										■		■	■	■	■
Oral Presentation, Poster exhibition, demo/simulation													■		
EDX (*if any)														■	
Submission of Final Report															■

*subject to change

CHAPTER 4

SECTION A

4.1 Data gathering

The assessment will begin with data gathering whereby all the data related to the pipeline i.e. design data, operational data, inspection data, pipeline drawings, history of the pipeline operations, materials data and other relevant information are gathered and checked for its accuracy. All these data are mandatory as they are inputs for the internal corrosion modeling. The more accurate it is, the more accurate the results will be.

The manner in which data is collected and later analyzed is represented in Figure 3. The pipe is first divided into sample areas for inspection (often determined by the inspection device scanner, in our case MFL Pigging). An individual sample area contains a number of individual values of thickness or pit depth taken by NDT device.

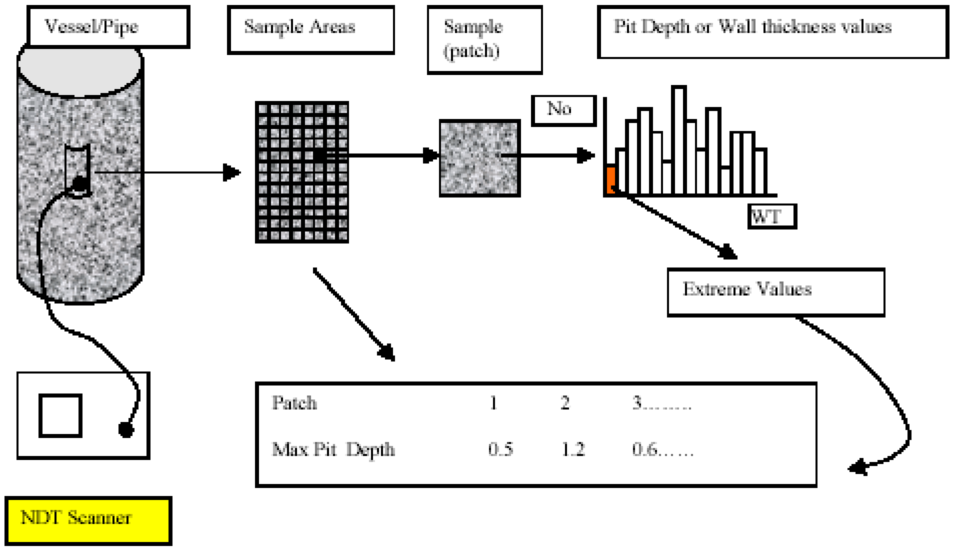


Figure 3: Data collection from a pipe to produce extreme values (Reference [9], Kowaka M: Introduction to life prediction of industrial plant materials)

4.2 Description of the corrosion data

4.2.1 Introduction

PMOPL24 is a 10” diameter pipeline with 6.9km length carrying wet and semi processed crude oil from KE-A platform to TI-A platform. It was built in 1982 and had a design life of 20 years. The original design life expired in 2002 and now it has been in operation for 25 years. The reported Maximum Allowable Operating Pressure (MAOP) is 40 bars which is de-rated pressure from 93 bars based on Fitness for Service (FFS) Assessment by PRSS/DNV in 2005. The pipeline is currently operating at average Operating Pressure (OP) of 28 bars. PCSB, PMO has requested PETRONAS Group Technology Solutions (PGTS) to perform FFS assessment to determine the pipeline integrity for this pipeline.

An inline inspection using Magnetic Flux Leakage (MFL) tool to determine the internal and external condition of the pipeline was conducted by Romstar in November 2006. The IP reported 10,804 metal loss defects with 10,803 internal defects concentrated at 700m from KE-A platform. There is only 1 external defect reported at KE-A riser.

For current integrity, it is found that 17 defects were having corroded pipeline pressure (P_{corr}) lower than MAOP with 8 defects were having P_{corr}=0 and there were 10 groups of interacting defects having P_{corr}=0. All the identified defects located within 100m to 350m section from KE-A platform.

For projected integrity, it is found that this pipeline had already challenged the corroded pipeline pressure against MAOP at the year of inspection, 2006.

4.2.2 Magnetic Flux Leakage (MFL)-pig

In-line inspections are performed by MFL-pigs also known as “intelligent pigs” that locate and characterize mechanical damages in pipelines. It is a common approach to the management of corrosion in the pipeline industry.

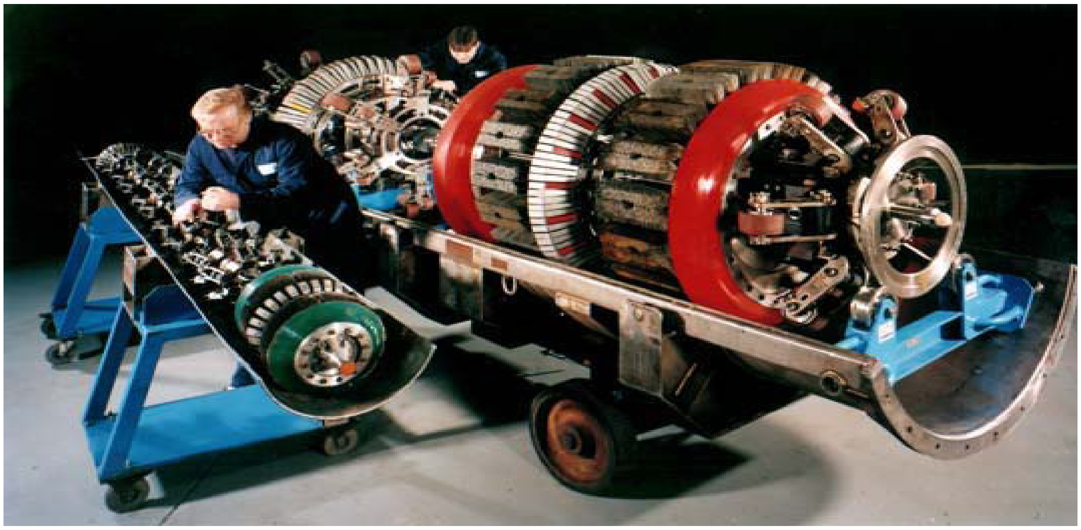


Figure 4: Small and large diameter MFL-pig

The pigging histories of PMOPL24 are:

Table 2: Chronological events on PMOPL24

Year	Event
1982	Installed & commissioned
1984	Intelligent pigging by Rosen
1993	Intelligent pigging by Rosen
1997	Intelligent pigging by Rosen
1998	Under water inspection by Sarku
1999	Under water inspection by Sarku
2002	Risk based inspection by PRSS
2003	Intelligent pigging by GE/PII
2005	Fitness for Service (FFS) by PRSS/DNV –Not fit for service Leak test at 40 bars to revalidate pipeline pressure De-rated system pressure from 93 bars MAOP to 38 bars Increase pigging frequency to weekly Increase chemical injection dosage
2006	Proposed several replacement options for approval Management requests to re-inspect the pipeline To check for growth on critical 2003 defects Intelligent pigging by ROMSTAR
2007	Engaged PGTS to perform FFS with latest intelligent pigging data – not fit for service Proposed for pipeline section replacement

4.2.3 Reported defects

The pipeline was inspected four times using intelligent pigging by Rosen (1993, 1997), PII (2003), and Romstar (2006). The first inspection by Rosen (1993) has 9 reported defects with a reporting threshold of 10%. The most severe defect is 21% defect depth due to mill defect while others are group under pitting. The second inspection was also done by Rosen (1997) and has identified 44 defects with a reporting threshold of 10%. The most severe defect is 17% defect depth due to pitting. The third inspection was done by PII (2003) and reported a total of 2186 defects with 2127 defects due to metal loss. The reporting threshold is 1% and the most severe defect is 45% defect depth which is classified under general type of defect.

Table 3: Summary of four IP data

Inspection year	**1994**	**1997**	**2003**	**2006**
Service provider	Rosen	Rosen	Pill	Romstar
Number of reported defects	9	44	2186	10896
Maximum defect depth (%)	21	17	45	46
Reporting threshold (%)	10	10	1	1

There is significant increase in the number of defects reported from year 1997 to year 2006. This is due to the fact that the reporting threshold for year 2003 and 2006 conducted by PII and Romstar respectively is 1% while for 1993 and 1997 conducted by Rosen has a threshold of 10%.

Also, there is no correlation between 4 sets of data. This is because the inspections were performed by different tools and IP service providers. Moreover, the MFL technologies have improved since.

4.2.4 Classification into defect type

The data was sorted into its defect features. The classifications are based on defects' width and length.

Table 4: Defect type

Defect type	Internal defect	External defect
AXGR	560	-
AXSL	203	-
CIGR	114	-
CISL	73	-
GENE	1243	-
PINH	2000	-
PITT	6610	1
TOTAL	10803	1

The following charts are the distribution of defects along the pipeline:

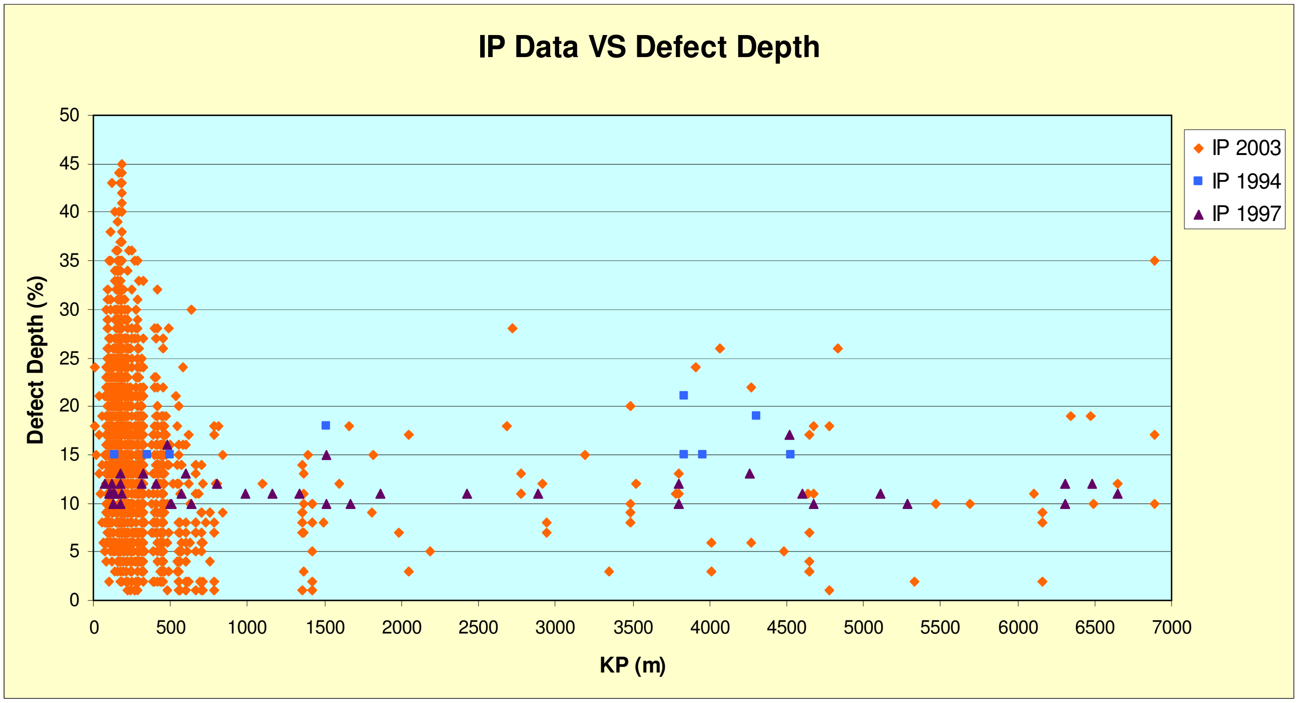


Figure 5: IP data vs Defect depth

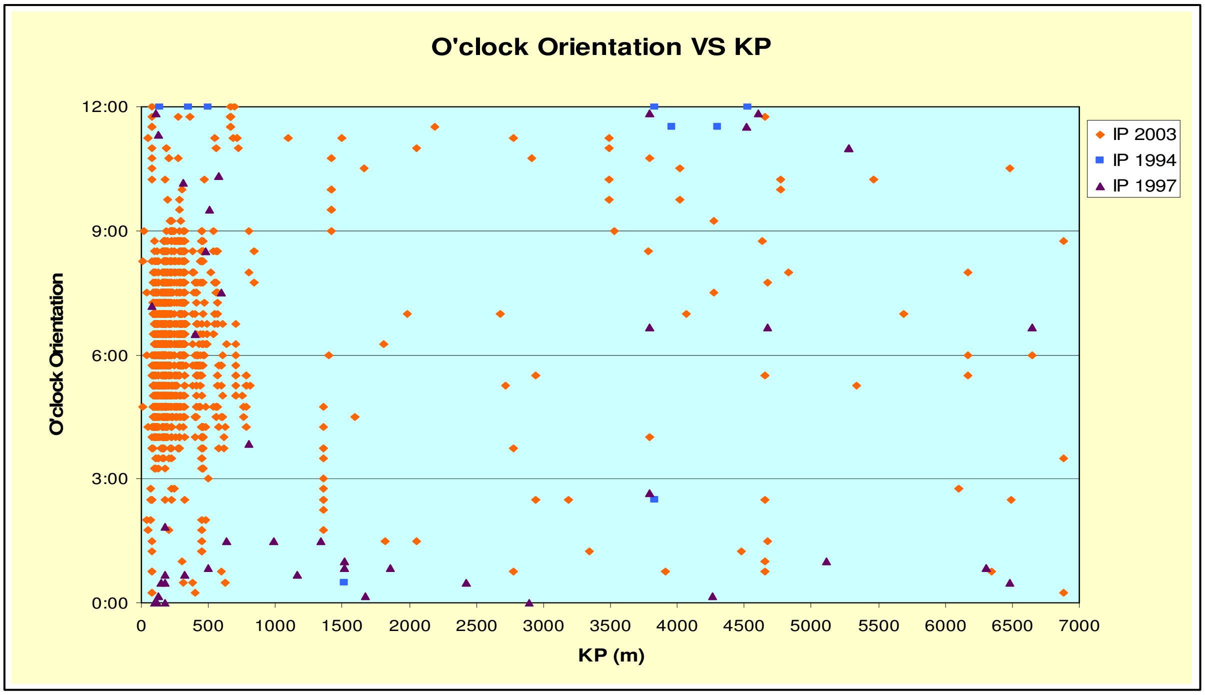


Figure 6: O'clock orientation vs KP

We can see that the corrosion are mostly concentrated at the first 700m of the pipeline from KE-A platform. Therefore in this final year project, the first 1km will be selected as the problem area to be studied further.To have a better look at the distribution of corrosion sites over the year, following are the grpahs break up from Figure:

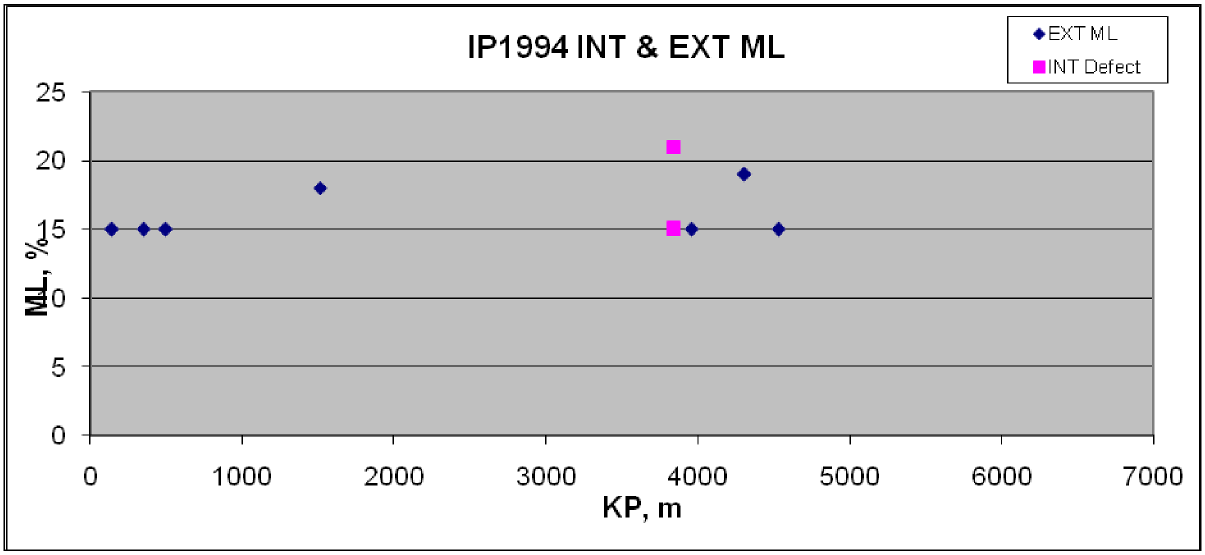


Figure 7: IP data year 1994

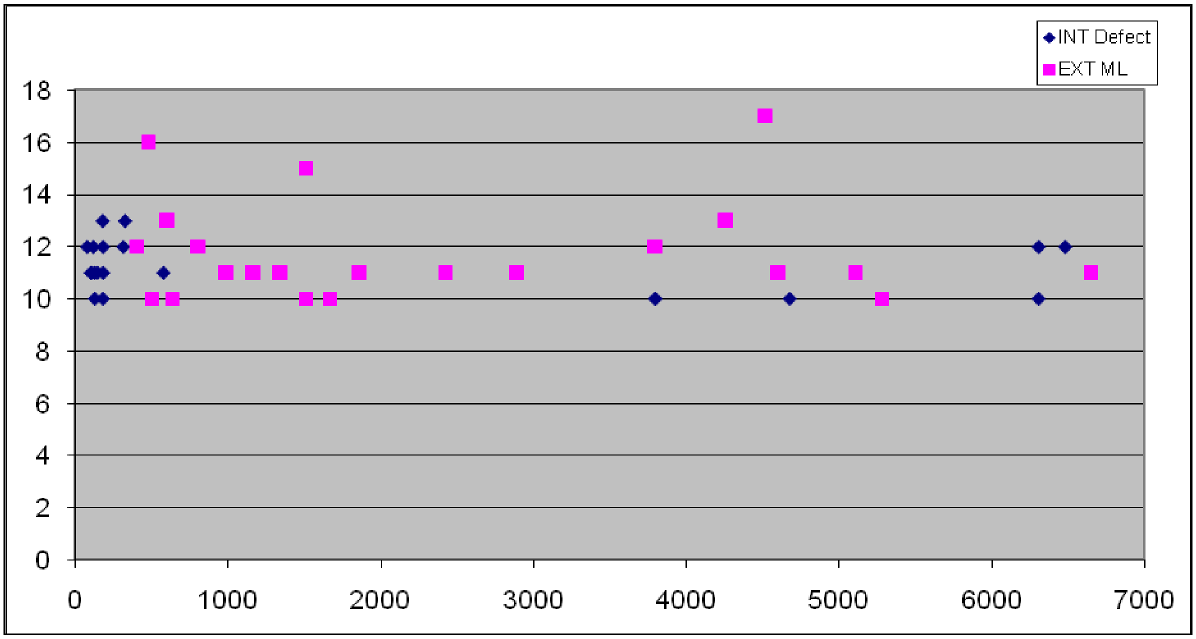


Figure 8: IP data for year 1997

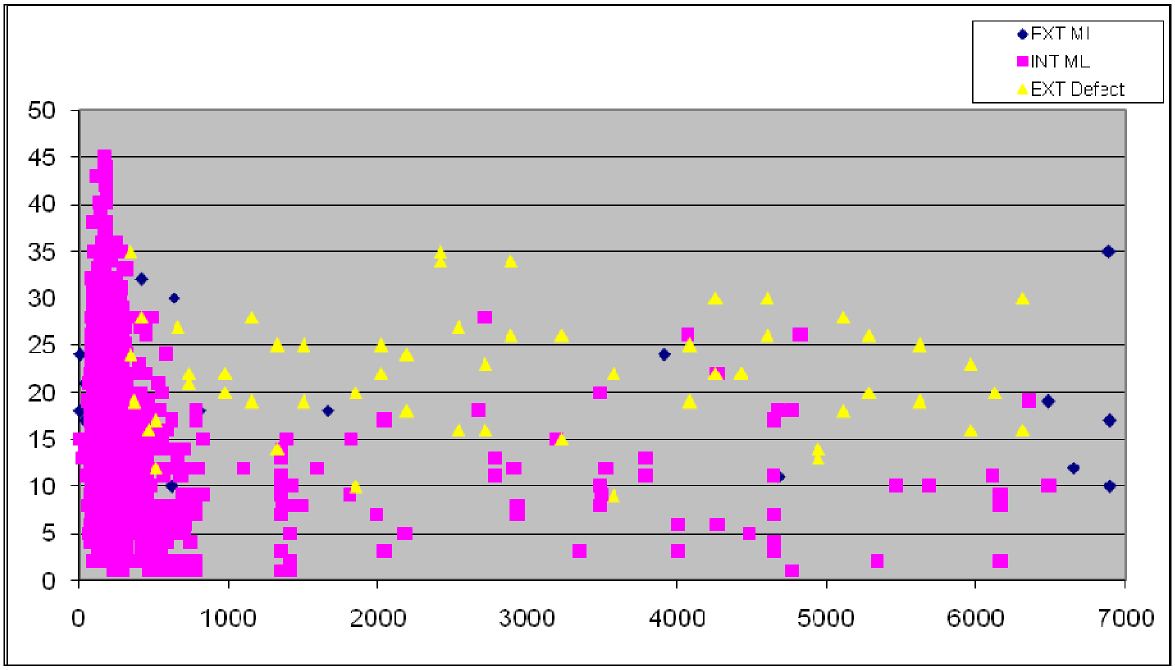


Figure 9: IP data year 2003

We can see from the graphs that the corrosion has increased exponentially after the year 1997. One of the reasons could be that the inspection interval was done after 6 years. Due to the difference in reporting threshold and the different IP service providers, there is the possibility of errors in identification. These possibilities are not looked upon in this project.

4.2.5 Operational Data

The pipeline was designed and operated under these conditions:

Design Data

Table 5: Design data for PMOPL24

Parameters	Unit	
Pipeline ID		PMOPL24
Pipeline Name		10” Crude oil KE-A to TI-A
Length	Km	6.9
Location		Offshore
Nom Diameter	In	10.75
	Mm	273.05
Nom Wall Thick	Mm	11.1
Material Type		Carbon steel
Material Grade		API 5L X52
Predominant Pipe Type		Seamless
Design pressure	Bar	103.5
	Psi	1501
Test pressure	Bar	145
	Psi	2103
MAOP	Bar	40 (de-rated)
OP	Bar	28 (average)
Product		Wet, semi processed crude oil
Installation year		1982
Design life	Years	20 (2002)
Design code		ASME B31.8
Design temp		-
Operating temp	^{o}C	55@Inlet, 30@outlet
Min water depth	m	65.5@ KE-A, 67.2@ TI-A

Table 6: Operational data for PMOPL24

Parameter	**Unit**	
Inlet temp	°C	55
Outlet temp	°C	30
Inlet pressure	Bar	28
Outlet pressure	Bar	25
CO_2	Mole %	1.8
H_2S	Mole %	0
CI availability	%	40(min) / 70 (max)
Total flowrate	m^3/d	488 (min) / 511 (max)
Crude oil flowrate	m^3/d	168
API gravity		27.5
Water flowrate	m^3/d	320 (min) / 343 (max)
Water cut	%	67
Inlet Fe count	ppm	0.02 (min) / 0.5 (max)
Inlet acetic acid	ppm	Data not available
Sand flowrate	kg/h	Data not available
Cl^-	ppm	3000 (min) / 3500 (max)
SO_4^{-2}	ppm	Data not available
S^o	% mass	Data not available
Inlet SRB count	cfu/ml	1-100
Outlet SRB count	cfu/ml	1

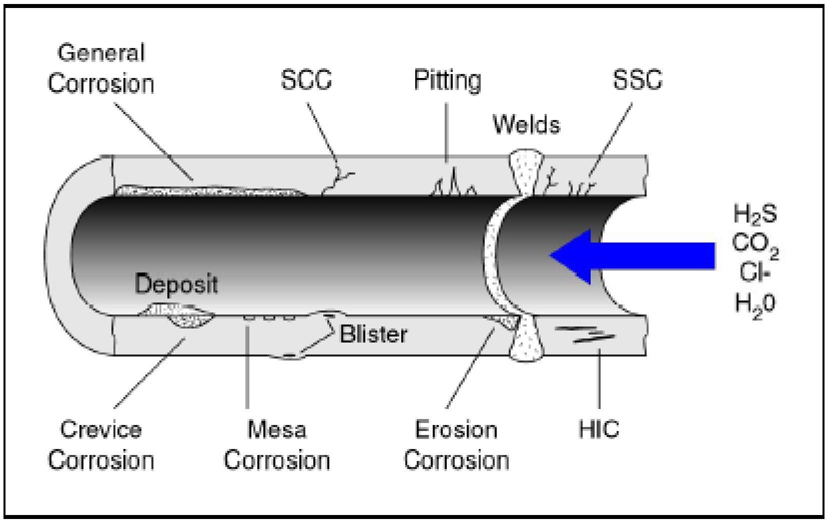
CHAPTER 5

SECTION B

5.1 Data Analysis

Corrosion can take many forms and the statistics shown of each will be different. The statistics arise from the measurements taken of the wall thickness of the component or the pit depth (when the surface is accessible). The morphology of the corrosion (the shape of the data) will affect these measurements and form them into distributions of data.

Figure 10: Different forms of corrosion



The analyses generally refer to areas where corrosion conditions are known to be alike. In general, to achieve these conditions the following must be similar:

- Materials
- Corrosion product/chemistry
- Temperature
- Flow rate

- Presence of inhibitor
- Fluid composition
- Presence of contaminants

It should be noted that small changes in these parameters can cause wide changes in corrosion rate. Normally, where conditions do change in the area to be inspected (e.g. welds) this can be handled by collecting data from these specific locations and treating them separately for analysis. However, in this case study, these parameters are not looked into and assumed to be irrelevant factors throughout due to lack of data.

Studies and applications of the statistical nature of corrosion, and its relationship to inspection have been carried out since 1950's but have never been commonly applied in routine inspections. No standards exist for the analysis of inspection data for corrosion. Initial work using extreme values was carried out by Gumbel [6]. He used the theory to estimate the condition of pipelines with external corrosion. Hawn [7] also used the extreme value method for external pits on pipelines; Joshi et al [8] use the extreme value analysis method to extrapolate from small inspection patches in an above ground storage tank and noted that the method particularly applied to pitting corrosion.

The methodology that underpins the extreme value statistical analysis of measurements of NDT inspection is defined fully by Kowaka [9]. Extreme value data sampling differs from fundamental data sampling in that the former only considers a set of extreme values extracted from a larger sample. Statistically, the effect of this filtering (i.e. using only part of the distribution) allows the tail of the resulting distribution to more accurately model the potential defect extremes which may exist in the material. In practice, to allow statistical integrity each extreme value must be collected from a subset of a large sample which in itself contains the sufficient data to infer a parent fundamental distribution population.

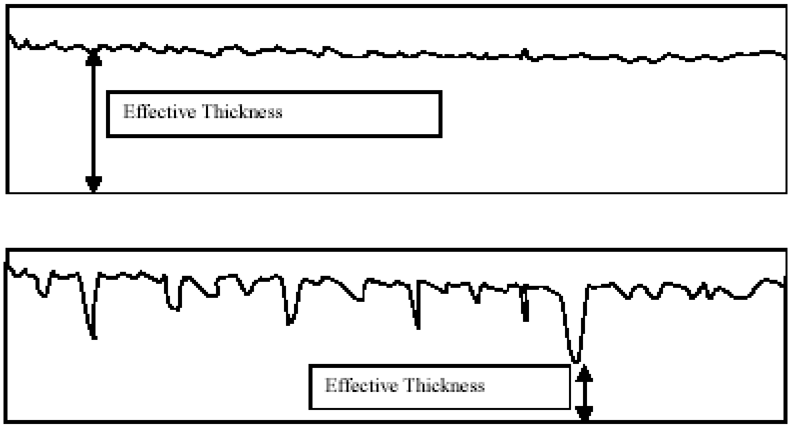


Figure 11: Top: Uniform corrosion, Bottom: Non-uniform corrosion

The upper example in Figure shows an example of uniform corrosion. Due to the uniformity of the defect, fundamental statistical distributions can be used to predict the average wall thickness loss.

The lower surface in Figure however shows an example of non-uniform corrosion displaying more localized defect penetrations. In this case, considerations of average pit depth are inappropriate since loss of containment will result as soon as one extreme defect perforates the material. Fundamental statistical distributions are not suitable for analysis of such cases, and extreme value calculations are required in order to predict the maximum expected pit depth from what will generally be sample information. The need for the use of extreme value distribution will be evident when NDT data is analyzed. In many experimental studies, the Gumbel extreme value distribution is used to model the deepest pits behavior.

5.2 Extracting Extreme Values

The extreme value type I distribution is also referred to as the Gumbel distribution. The extreme value type I distribution has two forms. One is based on the smallest extreme and the other is based on the largest extreme. We call these the minimum and maximum cases, respectively.

The general formula for the probability density function of the Gumbel (minimum) distribution is:

$$f(x) = \frac{1}{\beta} e^{\frac{-x-\mu}{\beta}} e^{-e^{\frac{-x-\mu}{\beta}}} \qquad (11)$$

Where μ is the location parameter and β is the scale parameter. The case where μ=0 and β=1 is called the standard Gumbel distribution. The equation for the standard maximum Gumbel distribution reduces to [10]:

$$f(x) = e^{-x}e^{-e^{-x}} \qquad (12)$$

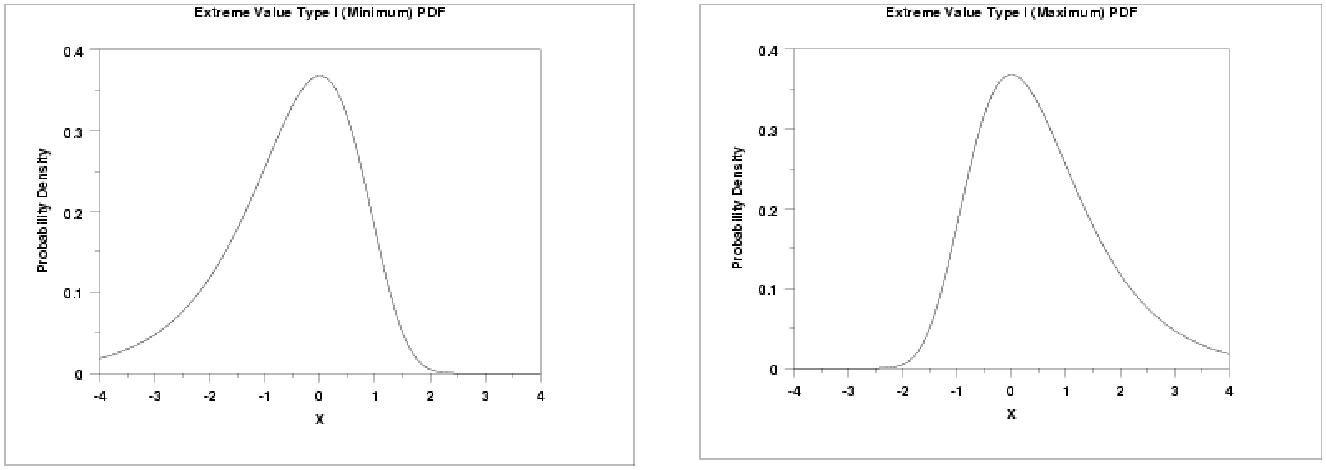

Extreme Value Type I (Minimum) PDF
Extreme Value Type I (Maximum) PDF

Figure 12: Plot of Gumbel probability density function

The formula for the cumulative distribution function of the Gumbel (minimum) and (maximum) is:

$$f(x) = 1 - e^{-e^{x}} \qquad (13)$$

$$f(x) = e^{-e^{-x}} \qquad (14)$$

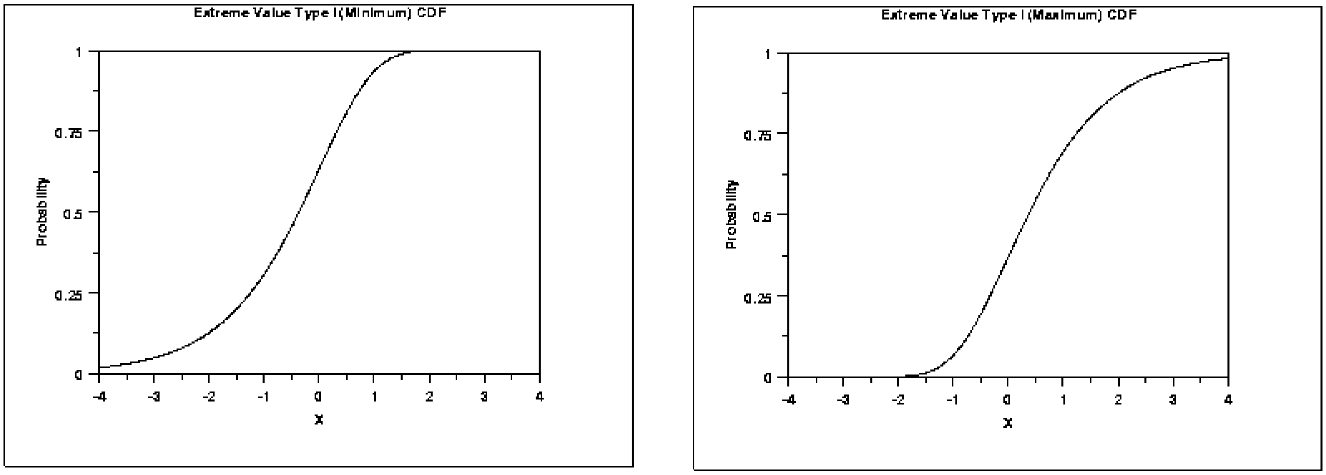

Extreme Value Type I(Minimum) CDF
Extreme Value Type I (Maximum) CDF

Figure 13: Plot of Gumbel cumulative distribution

CHAPTER 6

SECTION C

6.1 Corrosion Modelling

In this project, the corrosion model uses extreme value distribution because most corrosion is pitting. Using the data gathered from PMOPL24, we are able to classify defects into types and it is found that most corrosion is caused by pitting. In this case, the probability graph can be used directly to obtain an estimation of minimum thickness or maximum pit depth. From the inspection data from intelligent pigging, we are able to test the corrosion model from year 1994 to 2003 and verify it with data from year 2006.

6.1.1 Gumbel probability paper

The form of the Gumbel probability paper is based on a linearization of the cdf.

Gumbel max CDF:

$$F(t) = e^{-e^{\frac{-(t-\xi)}{\partial}}} \quad (15)$$

Rearranging the equations to read

$$F(t) = e^{-e^{\frac{-(t-\xi)}{\partial}}} = \frac{1}{e^{e^{\frac{-(t-\xi)}{\partial}}}} \text{ Or } \frac{1}{F(t)} = e^{e^{\frac{-(t-\xi)}{\partial}}} \quad (16)$$

Taking the log of both sides you get:

$$In\left(\frac{1}{F(t)}\right) = e^{\frac{-(t-\xi)}{\partial}} \quad (17)$$

Again, taking the log of both sides you get:

$$In\left(In\left(\frac{1}{F(t)}\right)\right) = \frac{-(t-\xi)}{\partial} = \frac{-t}{\partial} + \frac{\xi}{\partial} \quad (18)$$

y=mx + b

with y = $In\left(In\left(\frac{1}{F(t)}\right)\right)$, m = $\frac{-t}{\partial}$, c = $\frac{\xi}{\partial}$ (19)

6.1.2 Construction of Gumbel probability graph

Using WinSmith Software, we are able to easily fit the data into Gumbel Max graph: Taking the real time data, assuming that the maximum allowable corrosion allowance for the pipeline is 80%, this will give us 0.8*11.1 = 8.88mm. This means that the minimum thickness that the pipeline can sustain without rupture will be 11.1-8.88 = 2.22mm. This line can be seen in the graph as a line of warning.

Using the in-line inspection data from year 1997, 2003 and 2006, I am able to plot the graph and observe a corrosion pattern of the pipeline. I have decided to omit the data from 1997 and the years before because the limited amount of data shows no correlation, therefore are not helpful at all in the data analysis.

This can be clearly seen in the graphs below:

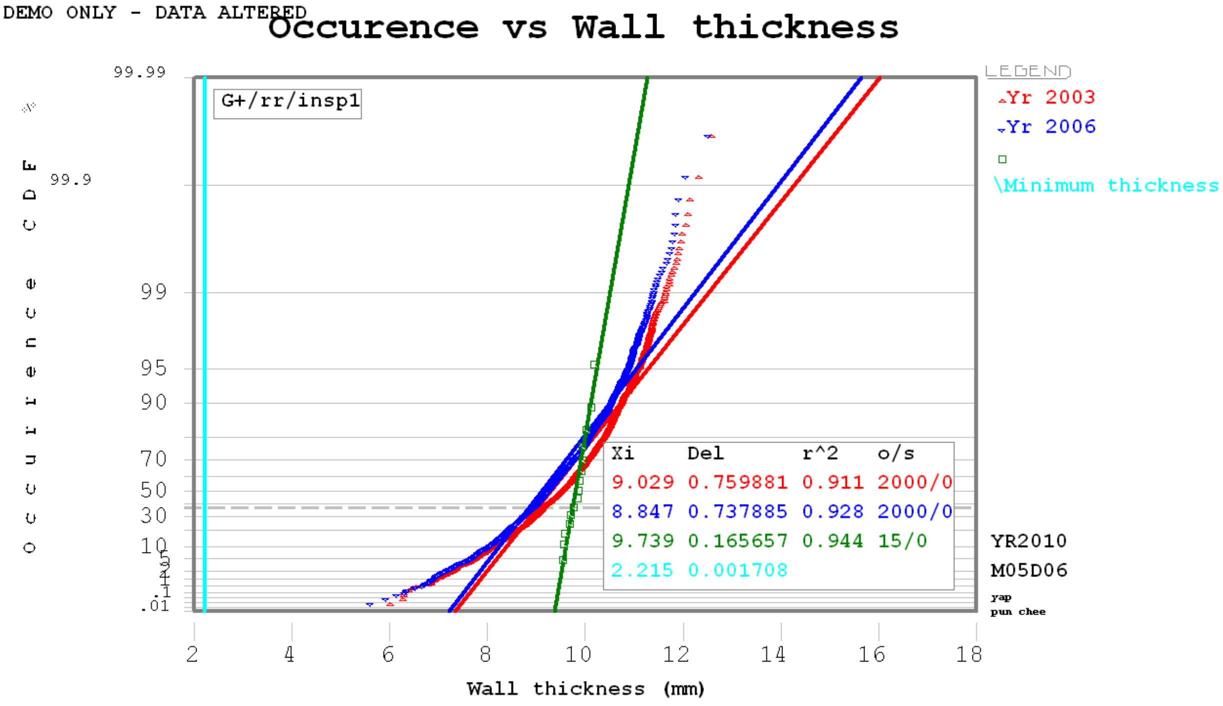


Figure 14: Gumbel probability graph with year 1997

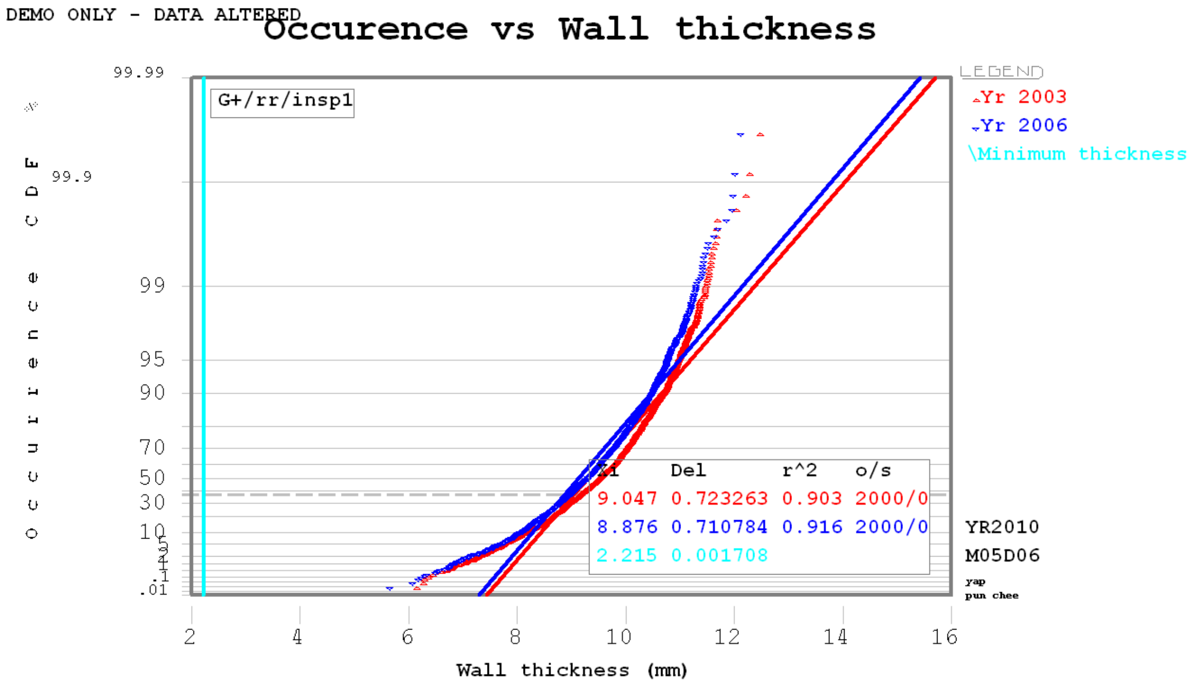


Figure 15: Gumbel probability graph without year 1997

Therefore, further analysis will be done using data from year 2003 onwards. From Figure 15, we can see that the corrosion pattern between year 2003 and 2006 are similar and can be assumed that following years of corrosion pattern follows the same. To predict the time to failure, prediction lines are drawn taking the same slope and tabulated over the years.

Graph below shows prediction of time to failure:

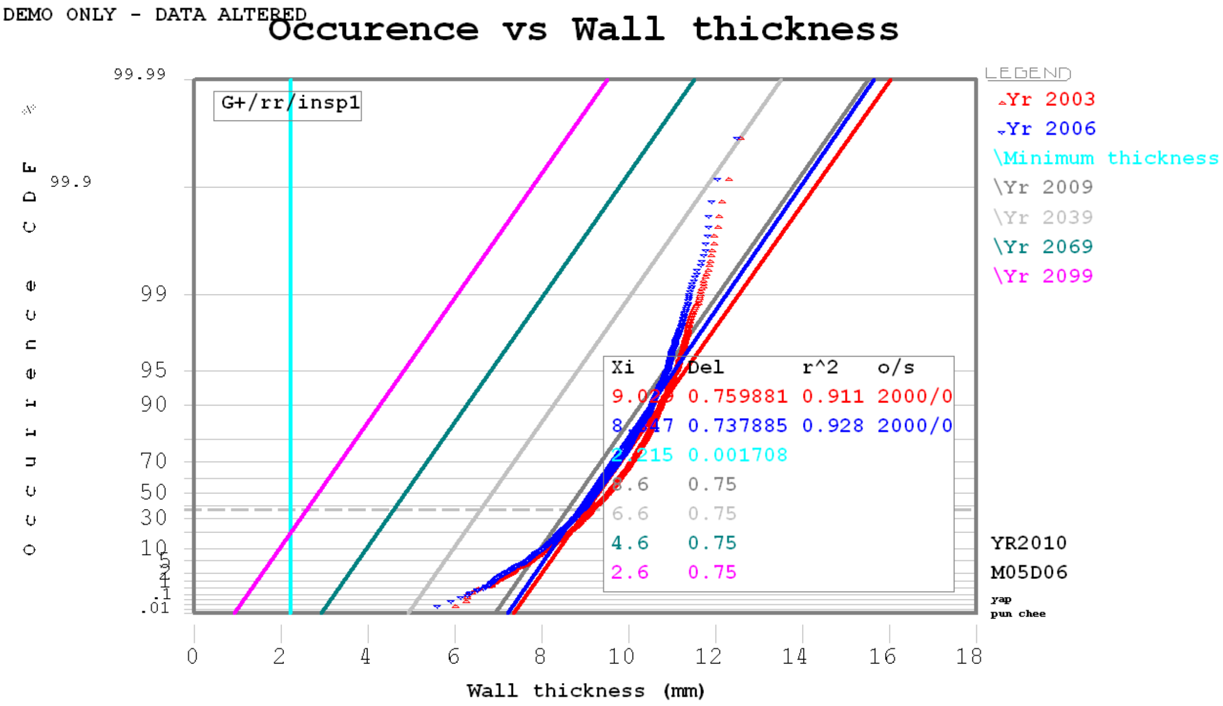


Figure 16: Forecasted time to failure

From the graph, we know that the predicted time to failure is at least another 60 years. To validate this predicted time to failure with the real time data, a deterministic approach was used to mathematically calculate the projected time to failure.

With the in-line pigging data, a series of calculations was used to determine:

Initial wall thickness: 11.1mm

Min wall thickness allowable: 80% CA x 11.1mm = 2.22mm

Wall Loss: (Defect depth/100) x Initial wall thickness
Actual thickness: Initial thickness – Wall Loss
Corrosion rate: Wall Loss/Years pipeline used
Time to failure: (Actual thickness – Min wall thickness)/Corrosion rate

Using these equations, I am able to determine the corrosion rate for every point of the defect recorded. The average time to failure is 149 years.

To calculate % error/deviation of both readings;

Time to failure from WinSmith: 93 years

Time to failure from In-line pigging data: 149 years

% error: (Actual- Reading) / Actual

: (149-93)/149

: ~38%

I would like to also point out that by using deterministic approach to calculate the time of failure will not be 100% accurate as we cannot record the exact point of corrosion every year. For example: Point A was recorded for inspection year 1994, the same corrosion point might be Point D in inspection year 1998. Therefore to monitor the pit growth and to calculate the corrosion rate per point is impossible. The deterministic approach calculates the point of corrosion recorded in every inspection and takes only the average time of failure.

Therefore, to fully reject this new method is to close door without investigating thoroughly. This method can be a more conservative model for corrosion prediction and it is easy to use. It is a quick way to study the corrosion pattern as well as the direct way of predicting the remaining life of the pipeline.

CHAPTER 7

DISCUSSION AND RECOMMENDATION

7.1 Discussion

7.1.1 Correlation between 4 sets of Inspection data

There are no correlations between the sets of data. We know that the inspection was done by different operators and due to the different reporting threshold; pigging technologies and the interval length, there are bound to be bias in the readings.

Because of this, it is decided that the in-line data from year 2003 onwards will only be considered. This is due to:

- Amount of data collected per year. Data collected from year 1994 to 1997 is too limited.
- Length of inspection varies. A gap of 6 years [1997, 2003] of inspection shows a great difference and with no data on what the flowing fluid is like, it is hard to make assumptions. Therefore the data before is ignored.

7.1.2 The exact location of corrosion pit cannot be monitored

In-line inspection reports corrosion sites the pig measured. The monitor the exact location of each pit/site is nearly impossible. For example: Point A was recorded for inspection year 1994, the same corrosion point might be Point D in inspection year 1998.

7.2 Recommendations

For a better study of this topic, it is recommended that more data is obtained. Data regarding fluid that flows through the pipeline, fluid flow conditions, and a wider range of pigging data is needed for a better study.

This method is feasible for a quick and easy way to identify the corrosion pattern of the pipeline and it can also provide a direct method of predicting the remaining life of the pipeline.

Therefore, it is worth pursuing and is a feasible method for corrosion prediction without any use of sample of your case study.

CHAPTER 8

CONCLUSION

In conclusion, the new approach for simulating a corrosion rate model using Gumbel is definitely feasible and worth exploring given that all information is available. The result using Gumbel predicts that the time-to-failure is for another 60 years and was later validated with the average time-to-failure obtained using deterministic approach, giving the marginal error of 40%. This project has met the objectives and can be further developed.

CHAPTER 9

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