

PREDICTION OF CO₂ CORROSION GROWTH IN SUBMARINE PIPELINES

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Abstract: The paper presents a probabilistic-based methodology for the assessment of a pipeline containing internal corrosion defects. Two different models have been used to predict the future CO₂ corrosion rates namely a linear growth and the deWaard-Milliams models. A probabilistic approach is used to analyse the behaviour of corrosion data obtained from in-line intelligent (ILI) pigging inspections. The outcomes are parameters represented by their corresponding statistical distribution. Due to the availability of these statistical parameters, a Monte Carlo simulation is used to calculate the probability of failure of the pipeline due to bursting failure. The existence of corrosion may reduce the maximum capacity of the pipe, as such causing leakage and bursting when the operational pressure supersedes its threshold. From the analysis of the result, failure probability based on theoretical linear growth model exhibit slightly longer lifetime of the pipeline with three years interval compared to deWaard-Milliams model. This is due to higher mean value of corrosion growth rate estimated using the empirical deWaard-Milliams model. Both results are very useful in prolonging the lifetime of pipelines by having knowledge of the past to schedule the future maintenance work.

Keywords: CO₂ corrosion, probabilistic, Monte Carlo simulation

1.0 Introduction

Submarine pipelines are still the most economical means of transporting hydrocarbon over long distances. It is accredited for its efficiency and ability during shipping an enormous amount of oil and gas from one location to another. However, due to many deterioration factors, pipelines failures may constitute serious hazards to the environment, assets and even humans due to explosion and leakage. It may also present a significant impact to heavy financial loss associated with lost of production,

contaminated groundwater, subsea repair or even to clean the polluted marine environment. Therefore, the urgency among the oil and gas operators to maintain high reliability of their pipelines systems has risen in recent years.

Corrosion is recognised as one of the most dominant forms of deterioration process and as one of the major causes for loss of containment in offshore pipelines (Papadakis, 1999). Metal loss of aging pipelines section is a direct result of corrosion activity and with time, downgrades the integrity, safety and its structural reliability. Corrosion of variety forms, may occur either internally or externally or both. In most cases for submarine pipelines, internal corrosion poses more significant threat to the pipeline reliability due to its complexity and difficulty to locate or repair. The CONCAWE Oil Pipelines Management Group's Special Task Force (Davis *et al*, 2000) reported that there have been eleven incidents that resulted in a gross spillage total of 516m³ in Western Europe in 1999. A total of a quarter of the accidents was caused by corrosion and resulting in a total spillage of 199m³ of hydrocarbon products.

The types of corrosion in offshore pipelines depend on the nature of hydrocarbon wells of either sweet or sour. The predominant corrosive agent in sweet wells is carbon dioxide (CO₂). It is generally known that, CO₂ corrosion is one of the most significant degradation mechanisms in pipelines (Hellevink and Langen, 2000) although corrosion due to sour products could be very detrimental. CO₂ corrosion is controlled by many parameters with a variety of uncertainties. Because of that, the prediction of CO₂ growth rates and the prediction of the residual strength of corroded pipes are also very uncertain. To study the growth characteristics, this paper propose a methodology for corrosion rate prediction and hence estimating the remaining strength of the pipelines using the probabilistic and reliability analysis. Comparisons have been made between these two models; linear growth model and deWaard-Milliams model to determine the most appropriate model to be used in the corroded pipeline structural assessment.

The objective of this paper is to predict the remaining lifetime of pipelines under internal corrosion attack by combining reliability analysis and corrosion growth model. We discuss two models namely; linear model and deWaard-Milliams model to quantify the corrosion rate in studied structure. Monte Carlo which is a common method used by the industry for reliability analysis of pipeline systems will be used to simulate the results (Melchers, 1997). The paper is organized into six sections. Prediction of corrosion rate due to metal loss corrosion is discussed in Section 2. In Section 3, a simulation based reliability analysis is described. Section 4 presents the structural failure analysis using RP-F101 DNV code to determine the allowable pressure for pipeline. The main findings of the study are summarized in Section 5. Finally, Section 6 concludes the paper with a brief discussion on methods and findings in this study.

2.0 Prediction of Corrosion Rate

In this study, extensive amount of pigging data recorded over a 6-year period based on three times inspection (*year 1, year 3 and year 6*) has been utilised in the analysis. A mechanical pig operated based on Magnetic flux leakage principle (MFL) was deployed

by third party during scheduled in-line inspection in North Sea area. These data provide information on the internal corrosion geometry such as depth, axial length, orientation, defect location and defect type. A data matching procedure has been carried out to locate the corresponding matched feature on every set of inspection data. In pipeline corrosion, linear model is generally used due to its simplicity particularly in the absence of more detailed pipeline information. However, an alternative method using corrosion growth model prediction such as the deWaard-Milliams could also be used in the pipeline assessment (Hellevink and Langen, 2000).

2.1 Linear Model

The corrosion growth rate is calculated by assuming a linear dynamic growth pattern as shown by Equation 1. Due to lack of information, linear model is always becomes preferable in estimating the growth rate especially for long term prediction (Noor *et al.*, 2007).

$$CR = \frac{d_{T_2} - d_{T_1}}{T_2 - T_1} \tag{1}$$

where;

- CR = corrosion rate
- d_{T_1} = corrosion depth in year T_1
- d_{T_2} = corrosion depth in year T_2
- T_1 = year of inspection T_1
- T_2 = year of inspection T_2

The linear corrosion growth is used to estimate corrosion depth and corrosion length, L at a future time T_3 , where:

$$d_{T_3} = d_{T_2} + (CR \times (T_3 - T_2)) \tag{2}$$

$$L_{T_3} = L_{T_2} + \left(CR \times (T_3 - T_2) \times \left(\frac{L_{T_2}}{d_{T_2}} \right) \right) \tag{3}$$

In reliability analysis, corrosion growth is considered as a random process. The availability of three sets of inspection-matched data as described above used to determine the distribution of the corrosion growth. One of the advantages of this method is that, the growth is estimated using the actual dimension of the defects in every inspection.

2.2 The deWaard-Milliams Model

The main advantage for deWaard-Milliams model application is that, the data feature-to-feature matching procedure can be avoided. This is because the model is capable of estimating the corrosion rates without considering the actual corresponding dimension of corrosion defect in later inspection such as in the linear model procedure. The rate of corrosion is estimated by:

$$V_{CR} = \frac{1}{\frac{1}{V_r} + \frac{1}{V_m}} \tag{4}$$

$$\log(V_r) = 4.93 - \frac{1119}{T_{mp} + 273} + 0.58 \log(pCO_2) \tag{5}$$

$$pCO_2 = nCO_2 p_{opr} \tag{6}$$

$$V_m = 2.45 \frac{U^{0.8}}{D_h^{0.8}} pCO_2 \tag{7}$$

where;

- V_{cr} = corrosion rate (mm/year)
- V_r = flow-independent contribution denoting the reaction rate.
- V_m = flow-dependent contribution denoting the mass transfer rate
- T_{mp} = temperature (°C)
- pCO_2 = partial pressure (bar)
- nCO_2 = fraction of CO₂ in the gas phase
- p_{opr} = operating pressure
- U = liquid flow velocity (m/s)
- D_h = hydraulic diameter of the pipe. (D-2t)

3.0 Reliability Analysis Methodology – Monte Carlo Simulation

Based on the estimated corrosion rates from both growth rate models, a reliability analysis has been carried out to compute the predicted remaining strength of corroding pipelines in later years. A Monte Carlo simulation has been chosen in the case study due to its capability in sampling from any type of probability distribution. The data used in the simulation is shown in Tables 1 to 3. Defect dimensions, corrosion growth rate and material properties of pipelines are treated as random variables to account for the

uncertainties in the simulation. CR_1 and CR_2 as shown in Table 1 are corrosion rates for the estimated growth from T_1 (year 1) to T_3 (year 3) using linear method and deWaard-Milliams model respectively. The distributions of corrosion depth and length in year 3 and 6 are shown in Table 3 which has been fitted to Weibull distribution and verified through a series of chi-square goodness of fit test and graphical method (refer to Figures 1 and 2). Figure 3 illustrates the flow of methodology employed to estimate structure failure probability.

Table 1 : Summary of corrosion rates

Variable	Model	Unit	Distribution	Mean	std
CR_1	Linear	mm/year	Normal	0.1924	0.2341
CR_2	deWaard-Milliams	mm/year	Normal	0.2721	0.0162

Table 2: Parameters for deWaard-Milliams model

Variable	Unit	Distribution	Mean	std
Temperature (T_{mp})	°C	Normal	55	5.5
Mean flow velocity (U)	m/s	Fixed	1.0	-
Mole fraction of CO_2 (n_{CO_2})	%	Fixed	1.0	-

Table 3: Statistical parameters used in the Monte Carlo simulation

Variable	Unit	Distribution	β	θ
Corrosion depth, d (year 3)	mm	Weibull	1.125	2.10
Corrosion depth, d (year 6)	mm	Weibull	1.210	2.14
Corrosion Length, L (year 3)	mm	Weibull	0.6635	13.80
Corrosion Length, L (year 6)	mm	Weibull	0.7907	18.10

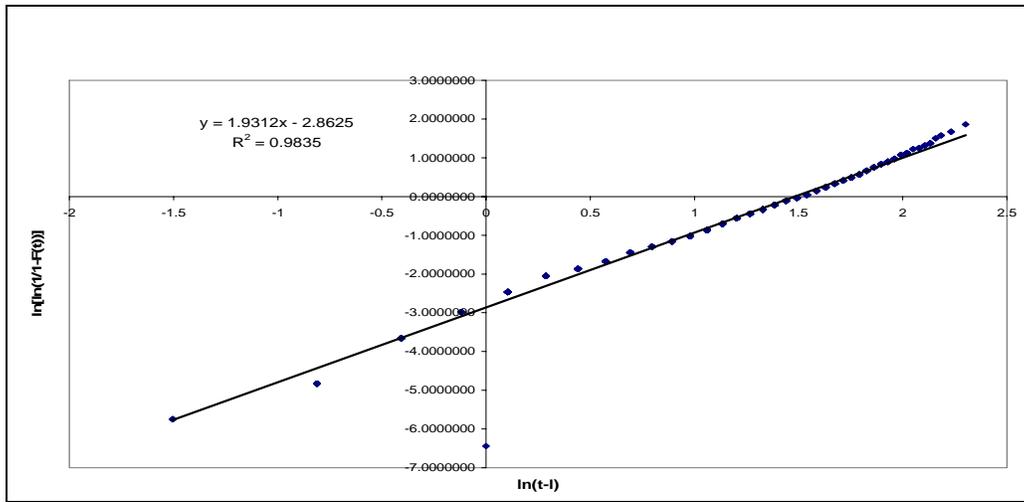


Figure 1: Weibull Probability plot of corrosion depth, T_6

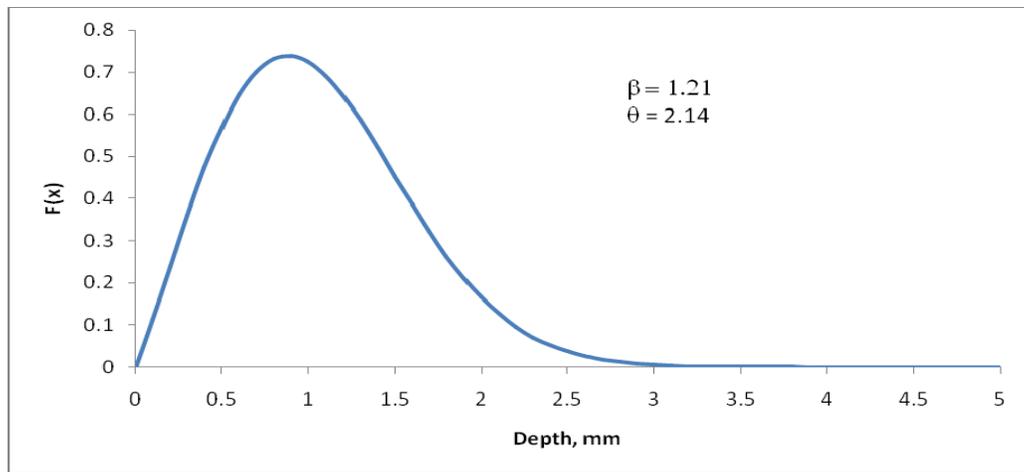


Figure 2: Weibull distribution of corrosion depth, T_6

Monte Carlo Simulation Procedure

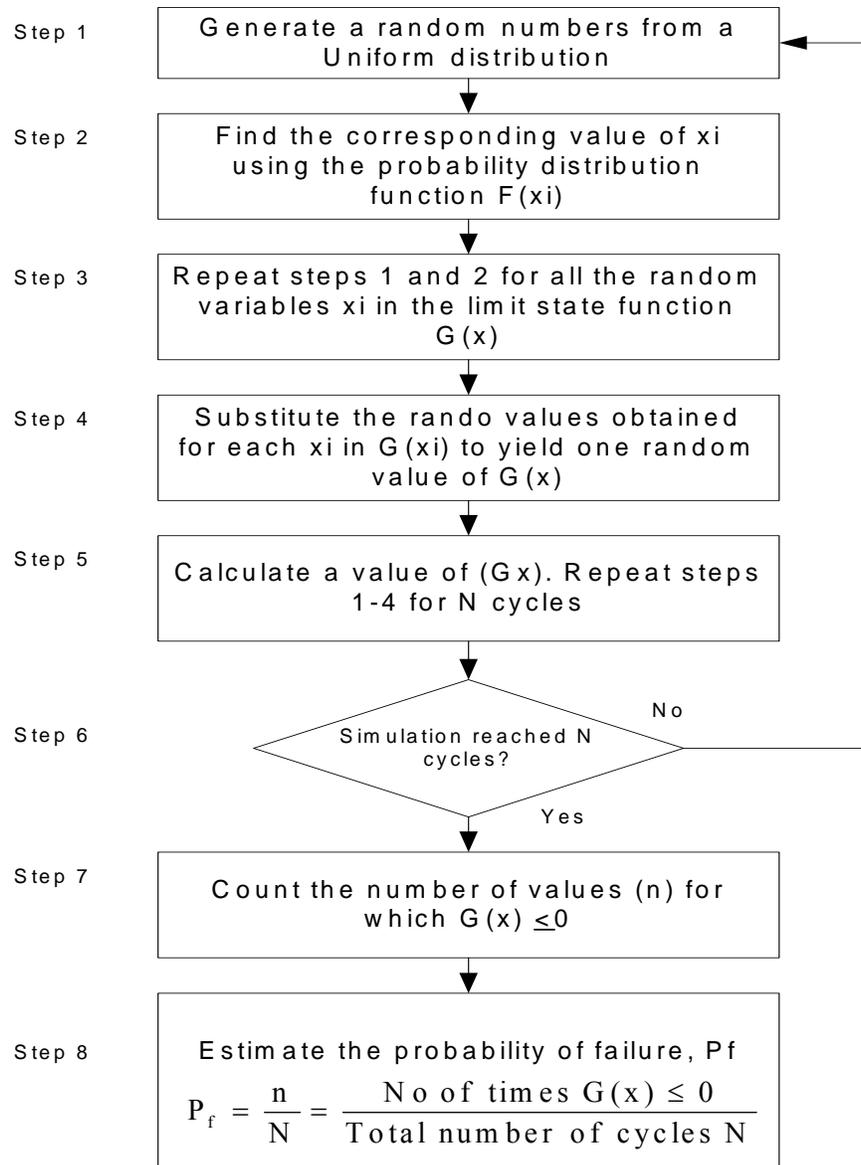


Figure 3: Procedure of failure probability estimation using Monte Carlo simulation method.

4.0 Structural Failures

A failure model RP-F101 specified by the Det Norske Veritas, has been used to determine the allowable pressure for pipelines (Det Norske Veritas, 2005). The choice is based on the merit that the equations in RP-F101 were derived using a probabilistic calibration, accounting for uncertainties in the defect measurements, and in the burst capacity (Cramer *et al.*, 1999), in-lined with the proposed procedure. The maximum allowed operation pressure in pipelines for a single defect is given in Equation 8. The material properties are as shown in Table 4.

$$P_p = \frac{\gamma_m 2tSMTS(1-\gamma_d(d/t)^*)}{(D-t)(1-\gamma_d(d/t)^*Q^{-1})} \leq P_{mao} \quad (8)$$

where;

$$Q = \sqrt{1 + 0.31[L/Dt]^{1/2}} \quad (9)$$

$$(d/t)^* = (d/t)_{meas} + \varepsilon_d StD[d/t] \quad (10)$$

D	=	outer diameter
d	=	depth of corrosion defect
t	=	pipe wall thickness
l	=	measured length of corrosion defect
$(d/t)_{meas}$	=	measurement of relative corrosion depth
γ_m	=	partial safety factor for prediction model and safety class
γ_d	=	partial safety factor for corrosion depth
ε_d	=	rupture value factor for corrosion depth
P_{mao}	=	maximum allowable operating pressure
$StD[d/t]$	=	standard deviation for measurement (d/t) ratio
$SMTS$	=	specified minimum tensile stress

Table 4: Material properties used in the reliability analysis

Variable	Unit	Distribution	Mean	COV (%)
Pipe Diameter, D	mm	Normal	914.4	5
Yield Stress, σ_y	MPa	Normal	459	5.6
Ultimate Stress, σ_u	MPa	Normal	573	5
Pipe Thickness, t	mm	Normal	22.2	5

The limit state function describes the failure criteria of the whole pipeline system. If P_p greater than P_a in Equation 11, negative values of $G(x)$ shows the failure of pipelines system. Vice versa, positive values for $G(x)$ imply safety.

$$G(x) = P_a - P_p \tag{11}$$

where;

- P_p = applied fluid pressure
- P_a = calculated allowable pressure using RP-F101

The two types of corrosion growth models described earlier, linear and deWaard-Milliams have been used to predict the future distribution of corrosion depths, hence estimate the structural integrity based on the remaining depth during the particular time. For linear model, the prediction used distribution of growth rate, which is based on the feature-to-feature growth model from *year 3* to *year 6* (CR_1). The deWaard-Milliams model also used to produce another distribution for corrosion rates called CR_2 (refer Table 1). The prediction of pipelines integrity has been carried out using defect depth in *year 3* and *year 6*. If the simulation is carried out in a number of cycles, N cycles, the probability of failure can be estimated using the expression in Equation 12.

$$P_f \approx \frac{n(G(x) \leq 0)}{N} \tag{12}$$

where;

- P_f = probability of failure
- $n(G(x) \leq 0)$ = number of trials which violated limit state function.
- N = number of trials

The ‘acceptable’ probability of failure has to be benchmarked against the suitable target reliability level. The target reliability level for this case study was taken as 1×10^{-3} based on the normal safety class and the ultimate limit state as proposed by Sotberg *et al.* [1996] in the Submarine Pipeline Reliability Based Design Guideline.

5.0 Results

The results of Monte Carlo simulation using 1×10^5 cycles for the prediction of corrosion depth in *year 3* and *year 6* to estimate the probability of failure with time are shown in Figures 4 and 5 respectively. It is depicted that, the projection of future corrosion depth distribution based on deWaard-Milliams prediction model has violated the target probability (limit state failure) earlier than the prediction based on linear model. As such, the pipeline can be considered in structurally critical condition in 25th year as compared to period between 28th to 29th years for linear model (refer Figure 4). The predicted failure probability is as expected since the distribution of corrosion rates estimated using deWaard-Milliams model exhibits a higher mean value than corrosion rates obtained from linear model. Figure 4 also exhibits a clear indication of uncertainties by referring to the interval of predicted failure probability. The time to failure of the pipeline based on linear growth model yield a range between *year 28* to *year 29* due to vast deviation of corrosion growth rate from its central tendency; mean value (refer Table 2, CR_1). While for case study based on deWaard-Milliams model, the predicted time to failure started from *year 3* and *year 6* are both comparable owing to low deviation of corrosion growth data (refer Table 2, CR_2).

Comparing the estimation of structural integrity, a small difference of probability of failure is found between the linear and deWaard-Milliams model. Both Figures 4 and 5 exhibit the increase of probability of failure with time due to dynamic growth of defects. The uncertainties associated with the use of linear model such as equipment measurement errors and conversion of signals, in estimating the distribution of corrosion rates is believed can gravely affects the prediction accuracy. The referred pipelines in the case study may be subject to failure much earlier than anticipated since the actual failure probability can be higher due to other deterioration mechanisms such as third party accident, seismic activity, etc.

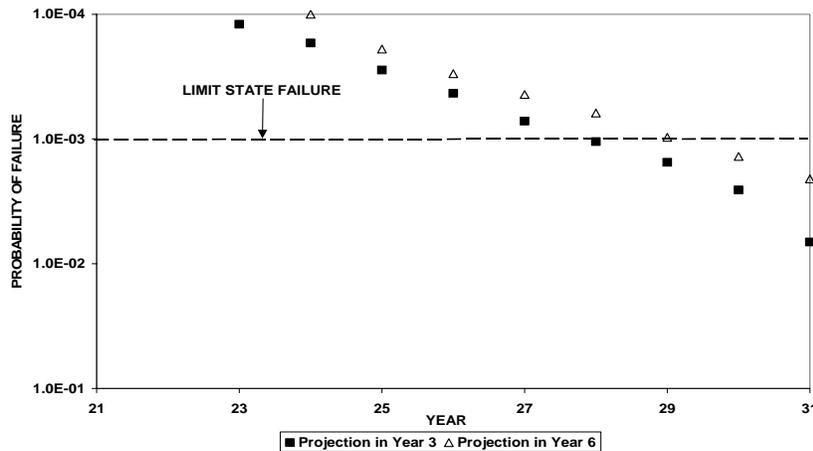


Figure 4: Projection of pipeline time to failure (Linear Model)

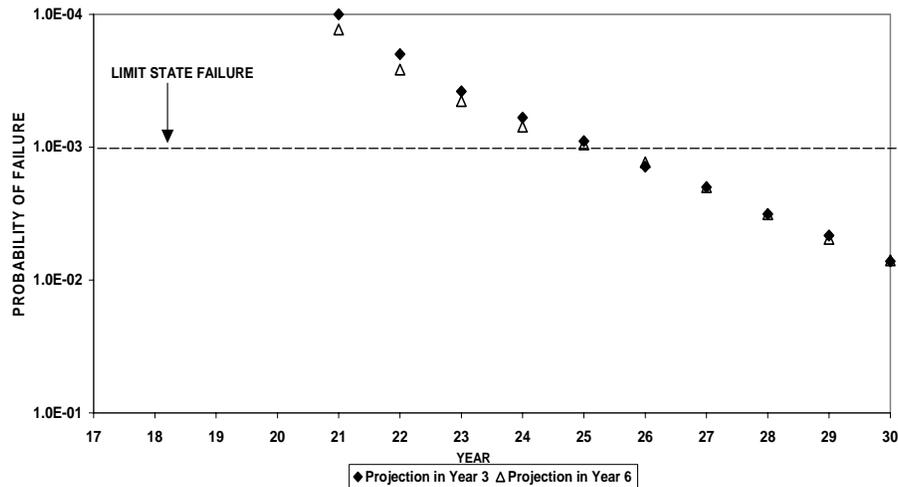


Figure 5: Projection of pipeline time to failure (deWaard-Milliams Model)

6.0 Discussion and Conclusion

The data obtained from in-line inspection using pig devices has many uncertainties owing to certain level of errors (Pandey, 1998). The existing uncertainties are difficult to be eliminated in the pipeline analysis and assessment. Therefore, the proposed probabilistic-based methodology is believed can effectively deals with these uncertainties. However, the methodology has illustrated a limited method to estimate the failure probability for the pipelines as it is based on internal corrosion only. In reality, the deterioration of pipelines is caused by many varieties of defect mechanisms such as internal erosion, free spanning, drop object, etc. that may lead to pipeline failure. Each of defect mechanism has its own failure probability that practically need to be considered in the analysis whereby the actual failure is expected to be at much earlier time in real event. The actual probability of failure can be represented by the total failure probability of all these defect mechanisms. Nevertheless, the assumption of structural failure based on the collapse due to wall thinning is acceptable as it is very commonly occurs in the field.

The imperfect dimensions of located defect results in inaccurate prediction of pipelines safety and integrity. Furthermore, the uncertainties associated with corrosion rate may have interfered the projection of corrosion growth. With appropriate sampling method, the estimation of corrosion rates based on feature-to feature sampling procedure can be improved [Yahaya *et al*, 2000]. Moreover, it is more money-worthy to fully utilise the repeated inspection data in the pipeline maintenance program by any operator. This work has demonstrated that, repeated inspection data can be used in the pipeline

assessment quite successfully. Therefore, unless a proper statistical correction procedure is carried out, deWaard-Milliams model is probably a better alternative to calculate the rate of corrosion.

Linear model is often used due its simplicity in estimating corrosion growth rate based on metal loss area [Din, 2008]. However, the accuracy of the estimated growth rate based on this model is greatly dependent upon the quality of inspection tools. While deWaard-Milliams model does not rely on metal loss data, the unknown variation of operational and environmental properties has always demoted the reliability of the equation. Having said that, both models can complement each other in this case study since the gap of pipeline time to failure is not more than three years. Under circumstance where environmental and production parameters are not readily available, multiple set of inspection data can be employed to estimate the metal loss rate. Proper prediction of pipeline integrity with high accuracy can assist operators to guard their pipeline against structural failures especially under unforeseen circumstances through well-planned schedule of future inspection, repair and maintenance program.

7.0 Acknowledgement

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