Stochastic modelling of perfect inspection and repair actions for leak-failures prone internal corroded pipelines.

Chinedu I. Ossai[*1], Brian Boswell[*2] and Ian J. Davies[*3]
Department of Mechanical Engineering, Curtin University, GPO Box U1987, Perth, WA 6845, Australia
[*1]ossaic@gmail.com,[*2]b.boswell@curtin.edu.au,[*3]i.davies@curtin.edu.au

Abstract

To enhance the performance of any facility, reduce cost and failure probability involves proper inspection and repair decisions. To be able to establish the cost of repair and inspection of corroded pipelines at different stages of the corrosion defect depths growth, Markov modelling technique was adopted. This model formulated an inspection and repair technique, which has the potentials of aiding policy makers in maintenance management of internally corroded pipelines. The transition states were determined using the Remaining Useful Life (RUL) of the pipelines whilst Weibull distribution was used for calculating the corrosion wastage rates at the lifecycle transition phases. Monte Carlo simulation and degradation models were applied for determining future corrosion defect depth growth, in a bid to establish periodic inspection and repair procedures and their costs. Data from an onshore pipeline inspected with Magnetic Flux Leakage (MFL) in-line-inspection (ILI) technique was used to test the validity of the model. The results obtained indicates that the model has practical applications for inspection and repairs of aged-internally corroded pipelines.

***Keywords**: Markov modelling; Lifecycle phases; Weibull distribution; Failure probability; Inspection and repair cost; Corrosion wastage time*

1.0 Introduction

Utilization of pipelines for transportation of oil and gas from production fields to refineries and loading terminals have resulted in the deterioration of the pipelines over time. This deterioration, which is caused predominantly by corrosion [1-3], results in pipe-wall thinning and reduction in reliability [4-5]. Although corrosion inhibitors and biocides have played a significant role in the reduction of the rate of pipe-wall thinning [6], the problem of pipeline corrosion, especially, internal ones, has significantly impacted the operations and maintenance cost of oil and gas companies as it accounts for over 50% of the downtimes in the industry [7-9].

The need to establish optimal inspection and repair policy is vital for risk quantification in operating oil and gas pipelines, hence, the reason why numerous researchers have worked on different aspects of risk optimization models for corroded pipelines [4-5, 10-13]. Gomes *et al.* [14] addressed inspection and maintenance optimization of corroded pipelines by using Monte Carlo simulation to sample and evaluate expected number of failures and repairs. These authors determined an optimal inspection and failure cost based on their model. The work of Wang *et al.* [15] also focused on estimating the reliability of corroded pipelines using finite element analysis and Monte Carlo simulation. This research, which determined the retained strength of corroded pipelines at different defect sizes was aimed at establishing the fitness-for-service of corroded pipelines. And also establish the optimal inspection and maintenance schedules that will ensure the safety of operations. Hasan *et al.* [16] also used Monte Carlo simulation and First Order Second Moment (FOSM) method to establish the failure probability of internal corroded oil and gas pipelines, after analysing the remaining mechanical hoop strength capacity of the corrosion defects. Sahraoui *et al.* [11] on their part proposed an inspection and maintenance policy, which was based on an imperfect inspection by considering the probability of corrosion defect detection and wrong assessment of defect sizes. These researchers had an ultimate aim of ensuring that the reliability of corroded pipelines is determined to a high degree of accuracy. Other researchers [13] approached corroded pipeline maintenance optimization for general corrosion, pitting corrosion and stress corrosion cracking from the point of failure frequency and the associated consequences of failure to health, safety and environment. They also optimized maintenance intervals in order to minimize cost. Again, Zhou [17] evaluated the reliability of corroded pipelines under the influence of internal operating pressure. The author modelled the reliability with respect to corrosion induced failures as - small leakage, large leakage and rupture.

Since corrosion is a function of uncertainties associated with the operating environment of the pipelines, it is always necessary to monitor the variability of the environment, materials and technique used for acquiring the data used for predicting the growth of corrosion defects of Pipeline [18-19]. To establish the deterioration arising from these external and internal constraints in a pipeline, a hierarchical Bayes framework, which used multi-level generalized least square was adopted for estimating corrosion defect growth while modelling the uncertainties in the operability of the material and environment [18]. Similarly, in order to optimize the service life of structures, a 2-stage inspection based maintenance management framework was used [20]. This technique, which considers deterioration defects and sizing error of detection of the defects, have the potentials of minimizing lifecycle cost of structures and optimizing the inspection intervals.

Optimal maintenance and repair planning involves the establishment of the acceptable failure probability level for the corroded pipelines, in consideration of cost. This also involves checking alternative inspection and repair policies, in order to establish the most appropriate for the expected pipeline reliability. Since the retained strength of corroded pipeline has direct link to the corrosion wastage at a given time, failure limit functions- leakage, burst and rupture have been established by different authors in consideration of stochastic corrosion growth rate [10-12]. Hence, managing corroded pipelines effectively entails, understanding the expected time of leakage, burst and rupture failures, as the corrosion wastage changes over time.

From the foregoing discussion, it can be seen that much has been done on reliability management of corroded pipelines. However, to the best of the knowledge of the authors, there have not been notable research on inspection and repairs optimization, in consideration of stochastic, probabilistic risk quantification. This situation motivated the authors to carry out such research using Markov modelling, Monte Carlo simulation and degradation modelling by focusing on the stochastic behaviour of corrosion defect depths. First order Markov chain modelling will be used in this paper for proposing the model, seeing that it has been used for establishing the effect of corrosion defect depth growth on corroded pipelines and other facilities by other researchers [21- 25]. The successful use of first order Markov chain modelling in different research areas such as corrosion has also made it an established principle for solving real life problems that requires sequence modelling, control tasks, machine learning and stochastic modelling.

This paper, therefore, aims to utilize information about corrosion wastage times to estimate inspection and repairs procedures for internally corroded pipelines, subjected to failure by leakage. As such, inspection and repair planning is expected to be done in consideration of the corrosion wastage times of the pipelines at the lifecycle transition phases – introduction-maturity, maturity-ageing, ageing-terminal, terminal-failure and failure-leakage. The objective of this research is to model stochastically, leak-prone pipeline failure by considering different inspection and repairs alternatives association with the corroded pipeline and estimate the cost. Even though numerous research works have been carried out on different aspects of inspection and maintenance cost models for corroded pipelines, the consideration of the lifecycle phases of corroded pipelines in inspection and repairs cost determination that is considered in this research is novel. Although we have assumed a perfect inspection that results in a non-significant measurement error of corrosion defects, it is important to note that the model developed in this research has a higher potentials of cost savings for inspection and repairs actions requiring leak failure. This is because other researchers have considered the threshold defect depth that will trigger inspection and repair of corroded pipelines as 50% [26] whereas this paper has taken this defect threshold as 80% in consideration of ASME standard [27]. Again, this research also considered the failure probability of the pipeline at different lifecycle phases in the determination of the survival probability, which is vital for estimating the inherent risk at any lifecycle phase of a corroded pipeline. It is also expected that the knowledge of the inspection and repair cost developed in this research will be useful for determining the future cost of pipeline integrity management as corrosion defect depths grows.

2.0 Markov modelling concept

A Markov Process is a stochastic system which has future events only depending on current ones without reference to previous events. This peculiarity makes a Markov Decision Process (MDP) to be memoryless since the impact of previous events on future occurrences are not recognized in predicting the future events [28-29]. The growth of corrosion defects of a pipeline has a typical memoryless system since the future corrosion defects growth rates and initiation locations on the pipeline does not depend on the previous corrosion defect sizes or spots. This is because the growth rates of existing corrosion defects and new corrosion defects initiation, depend on the characteristics of the operational parameters [2, 19, 30-32] that fluctuate with time and location on a pipeline. The interaction of the operating parameters and the pipeline material and specific behaviours of the corrosion process - stable and meta-stable states of a localized corrosion such as pitting [23, 33] also stochastically influence corrosion defects and contribute to the memoryless behaviour. The undependability of future corrosion defect depths on previous ones is the reason for the randomness of corrosion defects growth rates at different times for a given pipeline. This is why unique multi-corrosion defects growth rates and new defects initiation spots are identified during repeated in-line-inspection (ILI) as exemplified by different researchers [34-35].

If a discrete time stochastic process X_t, t=0, 1, 2, . . . is represented by a state space S, such that S = {0, 1,2, . . ., N_s-1} or {1, 2, . . ., N_s}, then for all *i* and *j* in *S*, the relationship in Equation (1) holds for a time homogeneous process [36].

$$P\{(X_{t+1} = j|X_t = i, X_{t-1}, \dots, X_0) = P\ (X_{t+1} = j|X_t = i)\} \qquad (1)$$

For a finite action set A = {a_1, a_2, . . .,a_n} and discrete time points t_0, t_1, t_2, t_i, t_{i+1}, . . . , the future state of the stochastic process X_{t+1} is independent of the previous states X_0, X_1, . . ., X_{t-1} but depends only on X_t and can be written as shown in Equation (2) for a 1-steps stochastic processes [36].

$$P^{(1)}(j|i,a) = P(X_{t+1} = j|X_t = i, A_t = a)_{\forall i,j\ \epsilon X_t, a \epsilon A, t=1,2,\dots} \qquad (2)$$

where $P^{(1)}(j|i,a)$ is the probability of a 1-step Markov process that the next state is in *j* at time *t+1* and the current state is in *i* and the action *a* is taken at time *t*.

For an m-step transition matrix with next state *j'* at a time *t+1* and action *a* is taken at current state *i'* and time *t* (Equation (3)), to be a stochastic matrix, the relationship in Equation (4) will hold, since there will be no inherent negative values in the Markov processes [36-37].

$$P^m_{i',j'} = \begin{bmatrix} P^m_{1,1} & P^m_{1,2} & \cdots & P^m_{1,Ns} \\ P^m_{2,1} & P^m_{2,2} & \dots & P^m_{2,Ns} \\ \vdots & \vdots & \ddots & \vdots \\ P^m_{N_s,1} & P^m_{N_s,2} & \cdots & P^m_{N_s,N_s} \end{bmatrix}_{\forall i',j'\ \epsilon S, a \epsilon A, t=1,2,\dots} \qquad (3)$$

$$\begin{cases} P^m(j'|i',a) \geq 0, \qquad for\ 1 \leq i',j' \leq N_s \\ \sum_{j-1}^{N_s} P^m(j'|i',a) = 1, for\ 1 \leq i' \leq\ N_s \end{cases} \tag{4}$$

In Markov decision process, a state space, S' = {S_1, S_2, S_3, …, S_t} remains in a particular state for a given exponential length of time and then transits to another state as shown in Figure 1 [37]. If the time for the transition from one state to another is such that the condition in Equation (5) holds,

$$\begin{cases} t_{i+1} = \min\{t > t_i | X_t \neq X_{t_i}\} \\ S_t = X_{t_i} \end{cases} \tag{5}$$

Then, the sojourn time {t_{i+1}-t_i} can be described using Markov's memoryless property according to Equation (6).

$$P\{(t_{i+1} - t_i) \leq t | S_0, \dots, S_{t_i}, t_0, \dots, t_i\} = P\{(t_{i+1} - t_i) \leq t | S_{t_i}\} \tag{6}$$

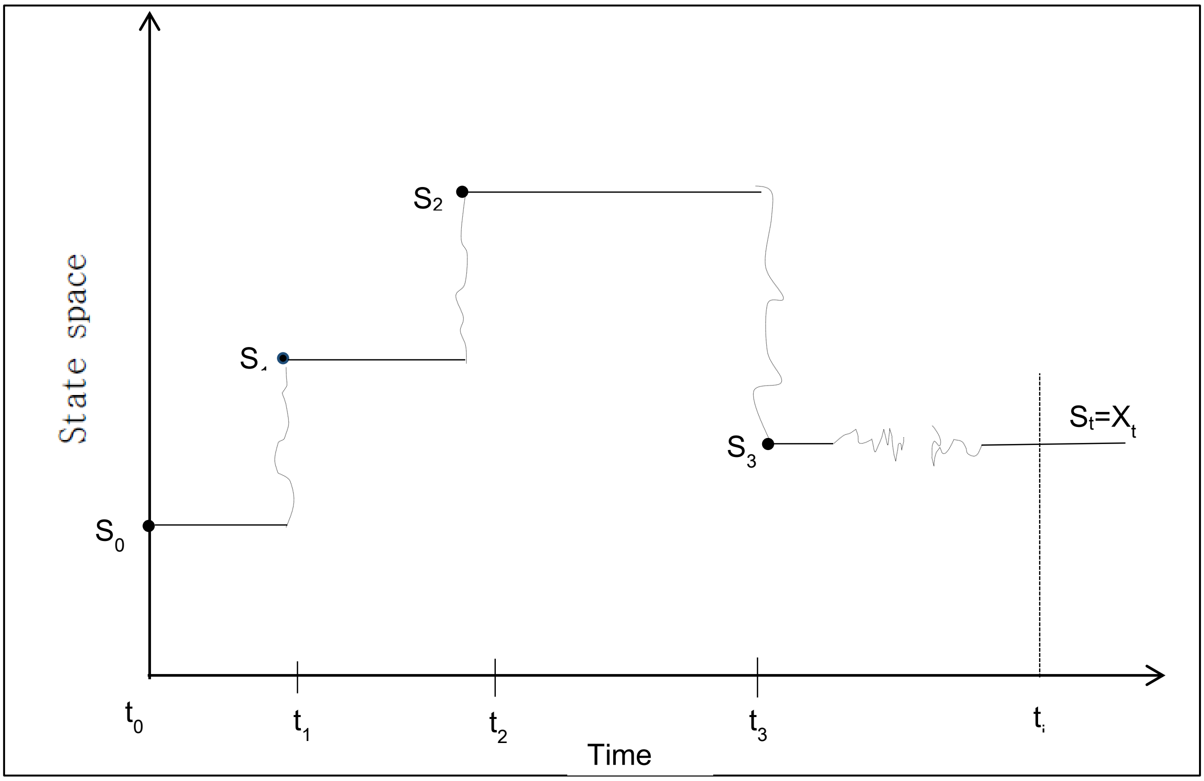


Figure 1: State transition & Sojourning time of a Markov Process

For a stochastic process, X_t under finite state space S' and transition times detonated as t_0, t_1, t_i, . . ., and space state denoted by S_0, S_1, . . . , there are scalar quantities μ(i) for i ϵ S that describes the mean sojourn rates as shown in Equation (7) [37].

$$P\{t_{i+1} - t_i \leq t | S_t = i\} = 1 - e^{-\mu(i)t} \qquad (7)$$

If R is the policy resulting from a set of decision processes such that R = {π_1, π_2, . . ., π_t} where π_t is the decision at time point t, the transition matrix ($P\pi_t$) and reward $r(\pi_t)$ at time t will be given as shown in Equations (8) and (9) [38].

$$P\pi_t = \sum_{a\epsilon A} P^m(j|i,a) * \pi_t^m(i,a)_{,\forall ij\ \epsilon S, t=1,2,\ldots,} \qquad (8)$$

$$r(\pi_t)i = r_t^m(i) * \pi_t^m(i,a)_{,\forall ij\ \epsilon S, a\epsilon A, t=1,2,\ldots,} \qquad (9)$$

For a finite planning horizon over a period N, a policy R and initial state i ϵ s, the expected total reward will be given by Equation (10).

$$V_i^N(R) = \sum_{t=1}^{N} \mathbb{E}_{i,R}\{r_t^m(A_t)\} = \sum_{t=1}^{N} \sum_{j,a} \mathbb{p}_{t,R}\{S_t = j, A_t = a\} * r_t^m(j,a), i \in S \qquad (10)$$

Where $\mathbb{E}_{i,R}$ is the expectation operator with respect to the probability measure ($\mathbb{p}_{t,R}$)at time t and reward R.

Over an infinite horizon, the expected total reward can be expressed as a function of the discounted rate ϒ, according to the expression in Equation (11).

$$V_i^{\Upsilon}(R) = \sum_{t=1}^{\infty} \mathbb{E}_{i,R}\{\Upsilon^{t-1}, r_t^m(A_t)\} = \sum_{t=1}^{\infty} \Upsilon^{t-1} \sum_{j,a} \mathbb{p}_{t,R}\{S_t = j, A_t = a\} * r_t^m(j,a), i \in S \qquad (11)$$

3.0 Characterizing Pipeline Lifecycle Phases

Assets generally deteriorate with years in operation with a resultant increased failure probability. However, ageing assets are more susceptible to failure due to the degradation of the material components of the assets. Pipelines degradation are caused majorly by stress-driven damages, cracking and fracture resulting from metallurgical and environmentally induced conditions that normally result in pipe-wall thinning [39-40]. This pipe-wall thickness reduction have been reported by many researchers to emanate from corrosion and erosion mechanisms going on in the pipelines [1-

3, 28]. In order to characterize the lifecycle phases of the pipelines, the pipe-wall thickness (P_{WT}) loss was used as a measure of the fraction of the Remaining Useful Life (R_{UL}) by recognizing the maximum corrosion wastage {$D_{max}(t)$} of the pipeline at a given time according to the expression in Equation (12). The lifecycle phases were later categorized into five stages [39] in consideration of critical milestones in the pipeline wall thickness loss.

$$R_{UL}(t) = 1 - \frac{D_{max}(t)}{P_{WT}} \tag{12}$$

Equation (13) and Figure 2 shows the variation of the lifecycle phases of corroded pipelines with the fraction of the remaining useful life.

$$\begin{cases} 0.9 \leq R_{UL} \leq 1 \;\; for\ S_{IM} \\ 0.7 \leq R_{UL} < 0.9 \;\; for\ S_{MA} \\ 0.4 \leq R_{UL} < 0.7 \;\; for\ S_{AT} \\ 0.2 \leq R_{UL} < 0.4 \;\; for\ S_{TF} \\ 0 \leq R_{UL} < 0.2 \;\; for\ S_{FL} \end{cases} \tag{13}$$

where S_{IM}, S_{MA}, S_{AT}, S_{TF} and S_{FL} represents the transition of the pipeline lifecycle phases between introduction and maturity, maturity and ageing, aging and terminal and terminal and failure respectively.

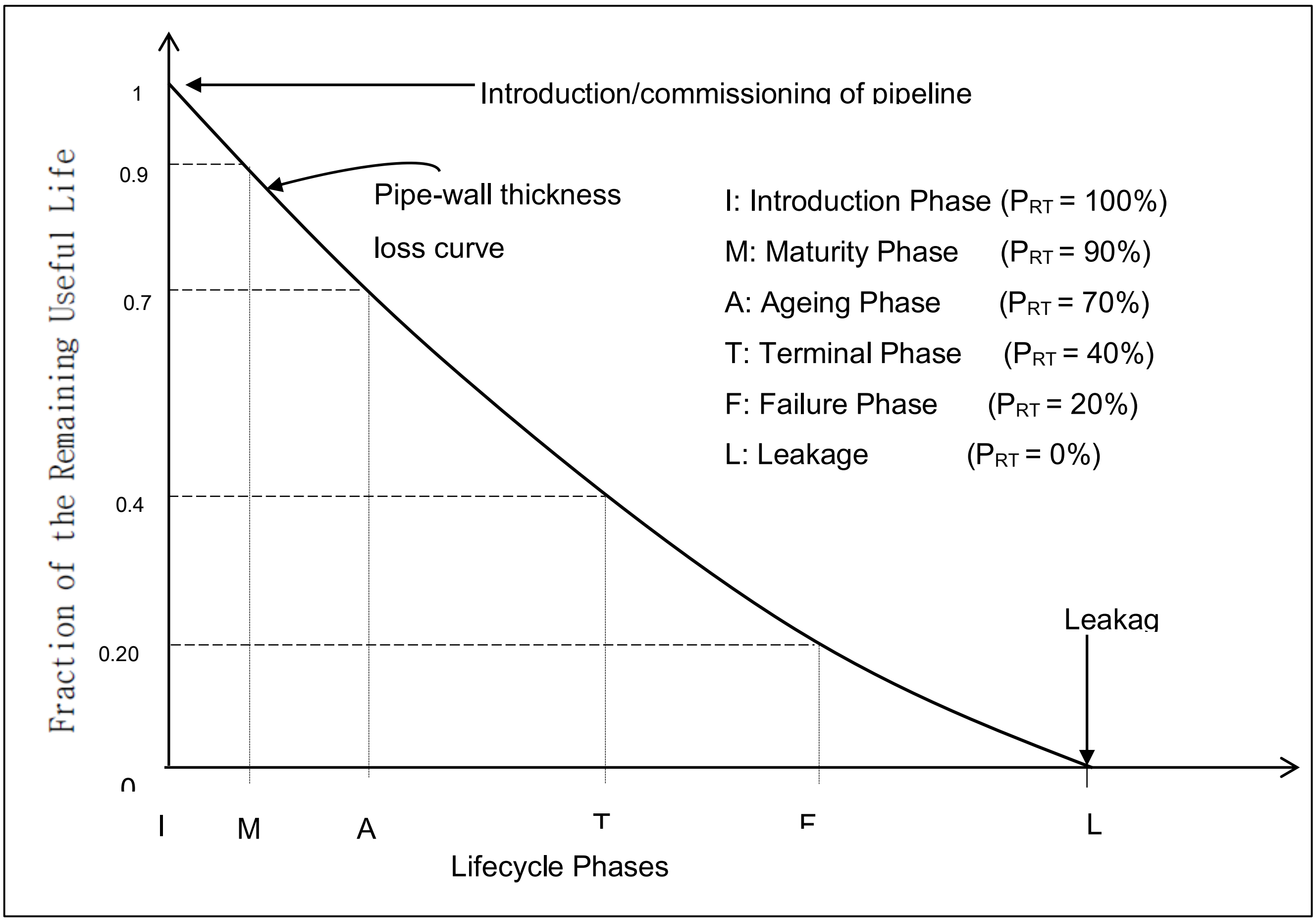


Figure 2: Variation of corroded pipeline lifecycle phases with the RUL

At the time of introduction/commissioning of a pipeline into operation, there is practically no significant corrosion process going on in it, since all necessary steps are taken to maintain the integrity of the pipes during construction of the pipeline. However, when the pipelines start transporting oil and gas, which could be in a multiphase flow regime after commissioning them into operation, the interaction of the corrosive species such as CO_2, H_2S, propionic acids, acetic acids, oxygen and chloride ion [2, 25, 31] with the carbon steel material of the pipeline results in a corrosion process [32, 41]. At the time of introducing the pipeline into operation, the pipe-wall thickness is intact as there is no corrosion process going on at this instant, hence, the retained pipe-wall thickness is 100%. As the pipeline commences operation, the passivity of the carbon steel material of the pipeline is destroyed over time due to the electrochemical and mechanical actions associated with the corrosive species [42-43] and other subcutaneous materials such as sand coming from the production wells [31, 44]. This destruction of the passivation of the carbon steel material of the pipeline normally results in the start of corrosion process, which brings about pipe-wall thickness loss over the lifecycle phase of the pipeline.

The corrosion of the pipeline can result in a uniform loss of pipe-wall thickness over time and localized loss of pipe-wall thickness at discrete random portions of the pipeline [41]. The rate of the corrosion of pipeline depends on some factors that includes the transport mechanism (flow rate), the characteristics of the pipeline material and the concentration of the corrosive species [2, 19, 30]. Corrosion generally affects the lifecycle phase of a pipelines, which depends on the amount of pipe-wall thickness loss over the duration of exposure to a corrosive environment. This implies that lower corrosion rates will result in longer time to loss the pipe-wall thickness, hence increased time to get to the lifecycle phases whereas higher rates of corrosion will result in the opposite effect.

The pipe-wall thickness loss due to corrosion results in distinctive lifecycle phases of the pipelines – Introduction, maturity, ageing, terminal, failure and leakage. The introduction phase of the pipeline lifecycle phase represents the time immediately after the pipeline is commissioned into operation with the pipe-wall thickness being intact. The maturity phase of the pipeline lifecycle phase follows immediately after the introduction phase of the pipeline. The maturity phase is reached when the retained pipe-wall thickness is 90%. The time between the commissioning of the pipeline and the time 10% of the pipe-wall thickness is loss to corrosion, helps experts to determine the corrosion wastage rate of the pipeline based on practical field data, obtained from different operational conditions. The corrosion rate information collected at this lifecycle phase of the pipeline is vital for planning Corrosion Risk Assessment (CRA) and In-Line Inspection (ILI) [45-46] while establishing whether or not the pipeline is corroding according to the design. Establishing the rate of corrosion of the pipeline at this lifecycle phase also guide the experts on the quantity and quality of corrosion inhibitors (if required), that will be necessary for maintaining the integrity of the pipeline [45, 47]. The corrosion rate between the introduction and maturity lifecycle phases of the pipeline has been shown to be higher than the corrosion rate at other lifecycle phases based on power model [35]. The ageing lifecycle phase of the pipeline is reached when the retained pipe-wall thickness of the pipeline is 70%. The transition between maturity and ageing phase is notable for stable corrosion wastage rate, due to the management practice applied to the pipeline. The corrosion rate at this phase is lower than that at the previous phase. At this phase, ILI is also scheduled in order to determine the areas of the pipeline that is affected by localized corrosion since, the predicted future corrosion rate is always based on general corrosion, which is uniform. At the terminal lifecycle phase of the pipeline, the retained pipe-wall thickness is 40% and the corrosion wastage rate continuous to decrease at the transition between ageing and terminal phases. Due to the reduced retained pipe-wall thickness of the pipeline at this phase, it is easier for the pipeline to fail if the corrosion defect is accompanied by other defects such as cracking, dents and out-of-roundness. At this lifecycle phase, ILI is performed at a more frequent rate than the other lifecycle phases due to the increased risk of failure of the pipeline.

At the failure lifecycle phase, the retained pipe-wall thickness is 20%. Although the pipeline may not practically fail at this phase if there are no other corrosion defects, however, due to the increased risk of pipeline failure, the pipeline is monitored closely by experts. The rate of corrosion at this phase is lowest in comparison to the other phases [35]. The pipeline is expected to leak when all the pipe-wall thickness is lost to corrosion at discrete defect spots, even for a pin-hole opening, however, it is never a practical option for operators of pipelines to allow the pipelines to leak but cost and operational constraints have repeatedly made it difficult to manage the pipeline integrity by repairs, maintenance and replacement [15].

3.1 Remaining Useful Life and Failure probability of Corroded Pipeline

The remaining Useful Life (RUL) is vital for estimating the retained strength of pipelines at a given time in consideration of corrosion defects [10]. Hence, monitoring the remaining pipe-wall thickness using techniques that includes in-line inspection, on-line inspection, risk based inspection and process control [12] are vital for risk quantification and safety estimation during the service life of the pipeline. To forestall catastrophic failures and prevent pipeline leakages, different regulatory agencies for the oil and gas sector have set benchmarks for determining the strength of defective oil and gas pipelines such as those undergoing internal corrosion. These standards which guide experts in predicting the strength of the corroded sections of the pipelines have been based on the remaining pipe-wall thickness hence, the reason for choosing the remaining useful life for categorizing pipeline lifecycle phases.

Utilization of pipelines for oil and gas gathering results in deterioration, which is commonly caused by corrosion and erosion as was previously stated, however, inspection and repair actions have the ability to reduce the effect of the corrosion and erosion actions [6, 48]. Although worn-out pipe-wall thicknesses cannot grow back on its own, but repair actions such as attaching of new sleeves and replacement of sections of corroded pipelines will result in the safety at such spots due to the additional wall thickness of the sleeve/replaced section. This repair action results in reduced failure probability at such corrosion defect spots as shown in Figure 3.

According to Figure 3, it is expected that when a pipeline is commissioned into operation at point A, presumably, without corrosion defects, it systematically losses its wall thickness over time until point B, when repair takes place at time t_n. Despite the fact that the loss of pipe-wall thickness will generally vary with the category of corrosion, the only major difference will be that, it will take shorter time to loss the same pipe-wall thickness for severe corrosion rate (>0.25 $mmyr^{-1}$) [49] than low corrosion rate of (<0.025 $mmyr^{-1}$) [49]. Since pipe-wall thickness loss due to corrosion can follow power law model [50], it is expected that pipe-wall loss at time t_{n+1} will be at point D, however, repair at point B resulted in the RUL of the pipeline at the defect spot being, at either C or E. It could be noted that point E could normally result from replacement of a section of the pipeline whereas point C could be as a result of localized repair using steel or composite sleeves. This repair action in point B will reduce the failure probability of the pipeline at the corrosion defect spot B, to E' or C' instead of D' expected for the defect spot, if no repair was undertaken (see Figure 4).

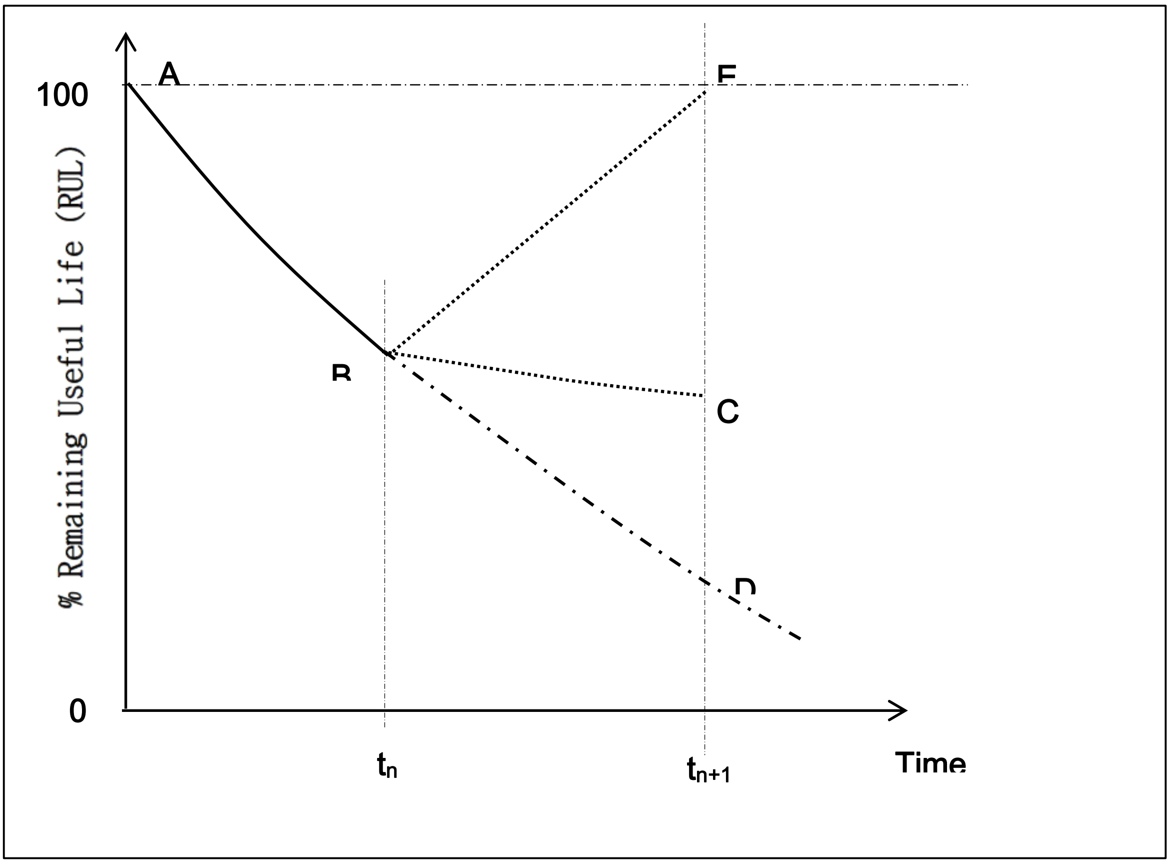


Figure 3: Effect of maintenance and repair on the remaining useful life of corrosion defect spots of corroded pipelines

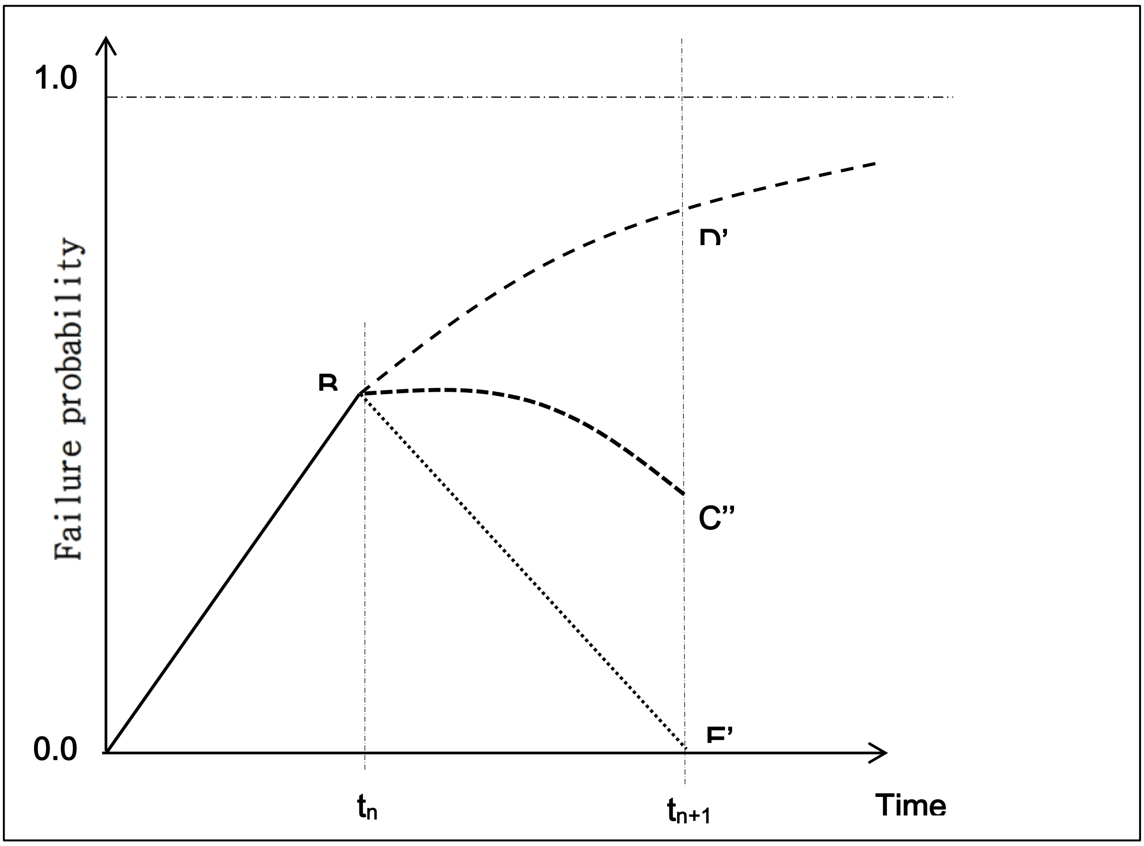


Figure 4: Impact of pipeline inspection and repairs on failure probability of a corroded defect spot

4.0 Modelling corroded pipeline inspection and repair actions

To effectively evaluate the effect of inspection and repairs on the lifecycle phases of pipelines, the pipe-wall thickness degradation rate with time of exposure of the pipeline to corrosion need to be considered. Since the RUL is a function of the remaining pipe-wall thickness after a given time of corrosion effect [8], the state space S of the lifecycle phases of the corroded pipeline have therefore been described as a function of the transition between different lifecycle phases with S = {S_{IM}, S_{MA}, S_{AT}, S_{TF}, S_{FL}}. As already shown in Equation (13), S_{IM}, S_{MA}, S_{AT}, S_{TF}, S_{FL} represents the fraction of the remaining pipe-wall thickness at 90% or more, 70% or less than 90%, 40% or less than 70%, 20% or less than 40% and 0% or less than 20% respectively. Again S_{IM} is termed to be an excellent condition of the pipeline whereas S_{MA}, S_{AT}, S_{TF} and S_{FL} represent good, fair, poor and unacceptable conditions respectively.

Three repair actions A = {a_1, a_2, a_3} are assumed to be predominant for managing the corrosion defect depths of the pipelines at different times of in-line inspection. Repair actions a_1, a_2 and a_3, which represents major repair, minor repair and no repair actions respectively, may be undertaken after ILI inspection on a spot having corrosion defect depth (d_i) depending on the pipe-wall thickness loss.

5.0 Markovian modelling of inspection and repair of corroded pipeline

Research has shown that pipeline corrosion may not always be uniform throughout the lifespan of a pipeline. For pitting corrosion, pit initiation, stabilization and meta-stabilization states, results in differential corrosion wastage rates at different stages of the pipelines lifecycle duration [23, 33]. Corrosion defect depths show a stochastic behaviour [23, 51], which makes it useful for using Markov's modelling for analysing the transition probabilities based on corrosion wastage rates.

5.1 Transition probabilities of inspection and repair actions

To establish the transition probabilities of the corroded pipeline at the stipulated lifecycle phases considered in this research, the following procedures were taken:

- Determine the statistical best fit distribution of the corrosion defect depths of the pipeline measured in the field.
- Utilize Monte Carlo simulation to establish the time lapse for the loss of the pipe-wall thickness due to corrosion.
- Estimate the parameters for corrosion wastage using the time lapse for pipe-wall thickness loss.
- Calculate the transition probabilities for inspection and repair actions using the parameters determined in the previous step.

5.1.1 Best fit statistical distribution of corrosion defect depths

The statistical best fit distribution for the corrosion defect depths were determined by testing distributions functions such as exponential, normal, lognormal, Weibull, Gamma, inverse Gaussian and generalized extreme value distributions. These distribution functions have been predominantly used for establishing the distribution of corrosion defect depths by other researchers [23, 33, 50-51]. Akaike Information criterion (AIC), which have also been used to determine the statistical best fit of corrosion defect depths [52] was used to establish the best fit distributions.

5.1.2 Time lapse of corrosion wastage of the pipeline

In order to establish the time lapse for the corrosion defect depth growth, Monte Carlo simulation, which utilized Poisson Square Wave Process (PSWP) described by other researchers [53-54] was adopted. The procedure, which involved the utilization of the statistical best fit of the corrosion defect depths for estimating future corrosion wastage of the pipeline, assumed that the time of corrosion wastage is independently exponentially distributed [13,53] and follows a Poisson arrival rate (λ_t). The cumulative corrosion wastage of the pipe-wall thickness and cumulative time for the wastage were collectively determined in the simulation process. However, the cumulative times for the corrosion defect depths growth generated by the simulation runs were utilized for establishing the parameters for determining the transition probabilities. The framework for the simulation process is shown in Figure 5.

5.1.3 Estimation of the parameters of corrosion wastage time

The corrosion wastage times estimated in the previous section were assumed to follow a Weibull probability distribution pattern shown in Equation (14) [55].

$$\begin{cases} \mathrm{f(t)} = \alpha\lambda(\alpha t)^{\lambda-1}e^{-(\alpha t)^{\lambda}}, & t > 0, \lambda > 0, \alpha > 0 \\ F(t) = 1 - e^{-(\alpha t)^{\lambda}}, & t > 0, \lambda > 0, \alpha > \\ 0 & \text{otherwise} \end{cases} \tag{14}$$

where λ, α, f(t), F(t) are shape parameter, scale parameter, probability and cumulative density functions respectively. Based on Equation (14), the corrosivity time (C_T) at the lifecycle phases of the pipeline is calculated according to Equation (15).

$$C_T = \alpha(-\log(\kappa))^{\frac{1}{\lambda}} \tag{15}$$

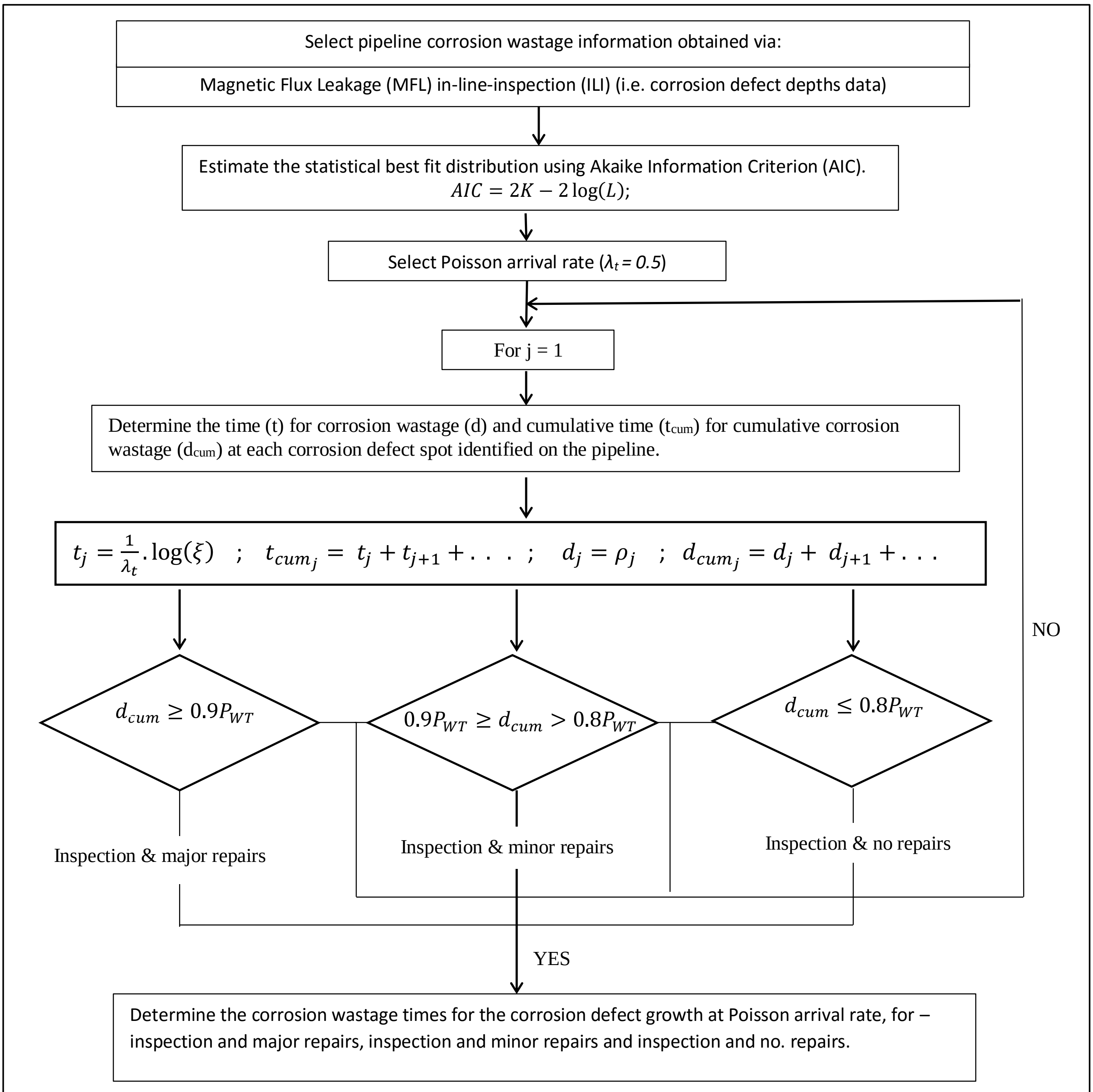
where κ represents the fraction of retained pipe-wall thickness at the lifecycle phases.

5.1.4 Transition probability at the lifecycle phases

The failure intensity (η) shown in Equation (16), determined by the Weibull parameters was used to calculate the transition probability (T_P) according to Equation (17).

$$\eta = \frac{\lambda}{\alpha}\left(\frac{C_T}{\alpha}\right)^{\lambda-1} \tag{16}$$

$$T_P = e^{-\eta C_T} \tag{17}$$



K represents maximum value of likelihood function; L represents number of corrosion defect depths; ρ represents random uniformly distributed numbers based on statistical best fit of the corrosion defect depths; ξ: uniform normal distributed random numbers between 0 and 1

Figure 5: Framework for Monte Carlo simulation of corrosion wastage time of corrosion defect depth

5.2 Probability of failure distribution

The time for failure (t_{fail}) of the pipeline due to corrosion wastage can be determined using Equation (18) [37, 56] whereas the survivor function ($R_s(t)$) at time t is shown in Equation (19).

$$t_{fail} = \min(t_{IM}, t_{MA}, t_{AT}, t_{TF}, t_{FL}) \qquad (18)$$

where t_{IM}, t_{MA}, t_{AT} ,t_{TF} *and* t_{FL} represents the cumulative lifecycle durations of the pipeline at introduction-maturity, maturity-ageing, ageing-terminal, terminal-failure and failure-leakage lifecycle phases respectively.

$$R_s(t) = P\left(t_{fail} > t\right) = R_{IM}(t).R_{MA}(t).R_{AT}(t).R_{TF}(t).R_{FL}(t) \qquad (19\ )$$

where R_{IM}, R_{MA}, R_{AT}, R_{TF} *and* R_{FL} represents the survivor function of the pipeline at introduction-maturity, maturity-ageing, ageing-terminal, terminal-failure and failure-leakage lifecycle phases respectively.

The survivor functions at the lifecycle phases of the pipeline are shown in Equation (20).

$$\begin{cases} R_{IM} = P(T_{IM} > t) = e^{-\eta_{IM}.t} \\ R_{MA} = P(T_{MA} > t) = e^{-\eta_{MA}.t} \\ R_{AT} = P(T_{AT} > t) = e^{-\eta_{AT}.t} \\ R_{TF} = P(T_{TF} > t) = e^{-\eta_{TF}.t} \\ R_{FL} = P(T_{FL} > t) = e^{-\eta_{FL}.t} \end{cases} \qquad (20)$$

where η_{IM}, η_{MA}, η_{AT}, η_{TF} *and* η_{FL} represents the failure intensity of the pipeline at introduction-maturity, maturity-ageing, ageing-terminal, terminal-failure and failure-leakage lifecycle phases respectively.

If the failure intensities at the lifecycle phase are random and independently occurring, the availability (A_{CR}) of the pipeline with respect to corrosion wastage at a future time (τ) can be expressed according to Equation (21) [56].

$$A_{CR} = \frac{1}{\tau}\int_0^{\tau} R_s(t)dt \qquad (21)$$

Equation (21) can be further simplified to Equation (22) whilst the probability of failure (P_{fail}) can be expressed according to Equation (23).

$$A_{CR} = \left(\frac{1}{\tau(\eta_{IM} + \eta_{MA} + \eta_{AT} + \eta_{TF} + \eta_{FL})}\right)\left(1 - e^{-(\eta_{IM}+\eta_{MA}+\eta_{AT}+\eta_{TF}+\eta_{FL})\tau}\right) \qquad (22)$$

$$P_{fail} = 1 - A_{Cr} \qquad (23\ )$$

5.3 Holding time over state-action pair

If the expected holding time for state action pair is given by ψ(i,a) for a finite decision horizon and ζ(i,a) for an infinite decision horizon, then Equation (24) gives the holding time of different lifecycle transition phases over a finite time of exposure T_{finite} and infinite decision horizon [36].

$$\begin{cases} \psi(i,a) = \sum_{t=1}^{T} P_{i,j}^{(t)}, \forall i,j\ \epsilon S, a \epsilon A, t = 1,2,..T_{finite} & , for\ finite\ horizon \\ \zeta(\mathrm{i,a}) = \lim_{t\to\infty} \sum_{t\to\infty}^{\infty} P_{i,j}^{(t)}, \forall i,j\ \epsilon S, a \epsilon A, t = 1,2,.. & , for\ \ infinte\ horizon \end{cases} \quad (24)$$

5.4 Inspection and Repair Cost

The cost of inspection and repair is expected to vary at different times over a finite decision horizon [56], however at an infinite horizon, the long run cost will be steady [36,57]. If the cost of a state-action pair is given by c(i,a), then the cost of inspection and repairs over a finite ($g_c(i,a)$) and infinite($L_c(i,a)$) decision horizons can be expressed as Equation (25) [36].

$$\begin{cases} g_c(i,a) = \psi(i,a) * c(i,a), & for\ finite\ horizon \\ L_C(i,a) = \zeta(\mathrm{i,a}) * \mathrm{c(i,a)}, & for\ Infinite\ Horizon \end{cases} \quad (25)$$

5.5 Pipeline inspection and repair policy

It was assumed that the internally corroded pipeline is subjected to failure by leakage at discrete points of the pipeline due to corrosion defect depth and a perfect inspection that results in non-significant measurement error existed. After Magnetic Flux Leakage (MFL) in-Line Inspection (ILI), the points on the pipeline that have gone beyond a certain threshold of the pipe-wall thickness is repaired based on the condition stated in Equation (26). For case 1, major repair action is undertaken whilst case 2 and case 3 results in minor repair and no repair actions respectively.

$$\begin{cases} case\ 1: 0 < d_i < 0.8P_{WT} & for\ a_3 \\ case\ 2: 0.8P_{WT} < d_i \leq 0.9P_{WT} & for\ a_2 \\ case\ 3: 0.9P_{WT} < d_i \leq 0.8\ P_{WT} & for\ a_1 \end{cases} \quad (26)$$

It was assumed that the repairs on the defect depths are done independently of each other, hence a corrosion defect spot can be subjected to major, minor or no repair after an ILI. The pipeline is assumed to be under general corrosion, which results in pipe-wall thickness loss of varying quantities at different spots. It was also assumed that the pipeline have no other defects that could result in burst and rupture in operation. Although the cost of failure by leakage may be small compared to burst or rupture failure [59], however, it is still pertinent to determine the expected cost of failure by leakage of the pipelines, as it also significantly contribute to operational expenditure of the company. The ILI inspection is expected to be scheduled based on the expected pipe-wall thickness loss prediction, but the inspection should be done at most every 5 years [59]. The ILI inspection will be scheduled before 5 years if the expected corrosion defect depth growth at corrosion defect spots are predicted to get to the threshold for repair (Equation (26)) prior to the 5 years of regular ILI. However, because of the cost associated with this process, if a defect spot is expected to get to any of the thresholds for minor or major repairs within 2 years from the time of ILI (based on modelling of the corrosion defect depths), it is repaired at that time of inspection. Again, it was assumed that any corrosion defect depth repaired by a minor or major repair will be as good as new. This is possible since, the replaced section of the pipeline in case of major repair or sleeve re-encirclement in case of minor repair will have available pipe-wall thickness that is equivalent or more than the original pipe-wall thickness. Based on this scenario, it is reasonable to assume that the quality of the repair job is good enough to support the pipeline for at least the entire duration of exposure of the pipeline prior to the repair. Hence, the assumption that after repair on a corrosion defect spot, it will not be repaired again until the pipeline is decommissioned. There is no inspection and repair required at the end of the service life of the pipeline.

5.6 Strategy for future inspection and repair cost evaluation

For an internally corroded pipeline subjected to periodic inspection and repair action, the cost of inspection and repair ($C_{IR}(t)$) at time t can be expressed according to Equation (27).

$$C_{IR}(t) = \left(C_{ILI} + C_{ma} \sum_{i=1}^{n_{ma}} d_m + C_{mi} \sum_{i=1}^{n_{mi}} d_n \right) (\gamma + 1)^t \qquad (27\,)$$

where $C_{IR}(t)$,C_{ILI}, C_{ma}, n_{ma}, d_m, C_{mi}, n_{mi}, d_n represents cost of inspection and repairs, cost of in-line inspection, unit cost of a major defect repair, number of major repair spots in a pipeline , corrosion defect depth needing major repairs, cost of minor repair of a defect, number of minor repairs in a pipeline and corrosion defect depth needing minor repairs respectively at the time of inspection t. The cost of inspection and repairs is shown in Table 1.

Table 1: Cost of Magnetic Flux Leakage In-Line Inspection of energy pipeline

Description of activity	cost($)	Remark
Major repairs	$1,500	for a given defect spot
Minor repairs	$800	
Inspection	$2900/km	

Source: [59-61]

The reward for inspection and repair action (R_{IR})at any of the lifecycle phase transition will depend on the total cost of in-line-inspection (ILI) and repair cost associated with either major or minor repairs. To establish the reward at each lifecycle phase of the pipeline, the expected duration of the lifecycle phases of the pipeline, the predetermined interval of ILI inspection (ℓ) and the cost of inspection and repair ($/Km-yr.) for the state-action pairs were used according to Equation (28).

$$R_{IR} = \frac{C_i}{\ell} * \begin{cases} t_{IM} \ , & for \ S_{IM} \\ t_{MA} - t_{IM} \ , & for \ S_{MA} \\ t_{TA} - t_{MA} \ , & for \ S_{AT} \\ t_{TF} - t_{TA} \ , & for \ S_{TF} \\ t_{FL} - t_{FT} \ , & for \ S_{FL} \end{cases} \qquad (28)$$

To predict the future cost of inspection and repair for an in-line inspected pipeline undergoing internal corrosion, Monte Carlo simulation and degradation modelling was employed to predict the corrosion defect growth over a specified inspection duration. The procedure employed is as follows:

- Generate future corrosion defect depths over a stated period T_{future}, for t_i, t_{i+1}, . . . ϵ T_{future}. Where t_i represents the time of initial future inspection after ILI.
- Determine the time of next ILI by considering the predicted future corrosion defect depths generated by Monte Carlo simulation or degradation modelling. Hence for predicted corrosion defect depths d_i, d_{i+1},d_{i+2}, . . .d_{i+n}, at inspection time t_i, establish the appropriate inspection and repair strategy based on Equation (26).
- Calculate the number of corrosion defect depths that require major and minor repairs.
- Determine the cost of inspection and repair at inspection times t_i and repeat the steps for inspection times t_{i+1}, t_{i+2}, . . . ϵ T_{future}.
- Compute the cumulative cost of inspection and repair at future time T_{future} by adding up the inspection and repair costs at inspection times t_i, t_{i+1}, . . . ϵ T_{future}.

6.0 A case study of internal corroded X52 pipeline

This model was tested on a 219.1 mm, 8.7 mm thick and 3.7 km API X52 grade gathering pipeline that was internally inspected using Magnetic Flux Leakage (MFL) in-line-inspection (ILI) in 2012. This gathering pipeline delivers multiphase fluid from oil and gas fields in the Niger Delta region of Nigeria and has 1034 corrosion wastage points dictated during ILI. The minimum and maximum pipe-wall thickness loss of the pipeline recorded during the inspection are 10% and 60% respectively.

Table 2: : Akaike Information Criterion (AIC) Values for different distributions pit depth

Distribution	AIC
Exponential	5270.30
Normal	3613.75
Gamma	**3545.99**
Weibull	3642.98
Gaussian Inverse	3550.49
Generalized Extreme Value	3556.77
Lognormal	7689.28

Table 1 shows the AIC values for the tested probability distribution functions. Since the lowest AIC value represents the best statistical fit [52], Gamma distribution with AIC value of 3545.99 represents the statistical best fit for the corrosion defect depths of the pipeline. Although research has previously shown that corrosion defect depth can be best fitted with Gamma distribution [35, 62], however, lognormal distribution [50, 53] and Weibull distribution [62] has been reported by other researchers as well. The probability density functions of the corrosion defect depths established with different probability distributions and the field data distribution of the corrosion defect depths are shown in Figure 6.

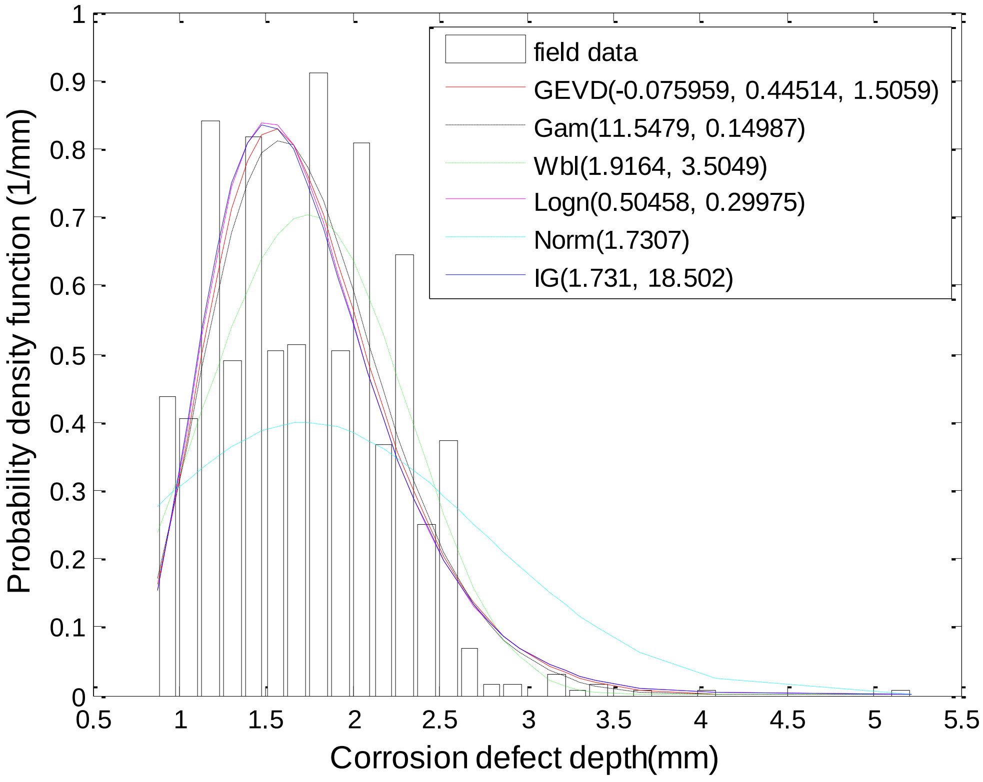


Figure 6: Field data and probability density distribution of the corrosion defect data for different probability density functions

6.1 Estimation of corrosion wastage parameters and transition probabilities

The Weibull parameters of the corrosion wastage time of defect depths for the various inspection and repair actions is shown in Table 3.

Table 3: Parameters of Weibull distribution

Inspection and repair action	Scale Parameter (α)	Shape Parameter (λ)
Inspection and major repairs	26.311	2.1863
Inspection and minor repairs	24.1053	2.2786
Inspection and no repair	22.277	2.554

The transition probabilities over a finite decision horizon computed for different inspection and repair actions using Equations (14) – (19) and information in Table 3 is shown in Table 4 whereas the steady state transition probabilities and failure intensities are shown in Table 5.

Table 4 : Transition Probability Over a finite horizon

inspection and minor repair action					inspection and major repair action					inspection and no repair action				
S_{IM}	S_{MA}	S_{AT}	S_{TF}	S_{FL}	S_{IM}	S_{MA}	S_{AT}	S_{TF}	S_{FL}	S_{IM}	S_{MA}	S_{AT}	S_{TF}	S_{FL}
0.7712	0.2288	0.0000	0.0000	0.0000	0.7386	0.2614	0.0000	0.0000	0.0000	0.6390	0.3610	0.0000	0.0000	0.0000
0.0000	0.5413	0.4587	0.0000	0.0000	0.0000	0.5046	0.4954	0.0000	0.0000	0.0000	0.4048	0.5952	0.0000	0.0000
0.0000	0.0000	0.3130	0.6870	0.0000	0.0000	0.0000	0.2860	0.7140	0.0000	0.0000	0.0000	0.2180	0.7820	0.0000
0.0000	0.0000	0.0000	0.1851	0.8149	0.0000	0.0000	0.0000	0.1682	0.8318	0.0000	0.0000	0.0000	0.1267	0.8733
0.9689	0.0000	0.0000	0.0000	0.0311	0.9707	0.0000	0.0000	0.0000	0.0293	0.9759	0.0000	0.0000	0.0000	0.0241

Table 5: Transition Probability (TP) and Failure Intensity (FI) of the state action pairs for the corroded pipeline

states	inspection and major repair action		inspection and minor repair action		inspection and no repair action	
	FI	TP	FI	TP	FI	TP
S_{IM}	0.0426	0.4258	0.0511	0.4037	0.0702	0.3507
S_{MA}	0.0558	0.2124	0.0655	0.2130	0.0856	0.2127
S_{AT}	0.0681	0.1418	0.0787	0.1478	0.0991	0.1619
S_{TF}	0.0766	0.1195	0.0877	0.1269	0.1080	0.1450
S_{FL}	0.0961	0.1005	0.1080	0.1087	0.1275	0.1297

Tables 5 indicates that the failure intensity of the pipeline increased with time of exposure to corrosion for all the inspection and repair actions. This is the trend expected from ageing assets, which have the survivability rates reduced with increasing age. Imperatively, the more a pipeline is exposed to corrosion, the more the probability of failure, despite the fact that the corrosion rates may be higher at initial exposure times and slower towards the terminal end of the corrosion wastage cycle of the pipeline [52, 55].

6.2 Failure probability analysis

Figure 7 shows the failure probabilities of the pipeline with time lapse of exposure to the corrosive environment. The failure risk of the pipeline varied with the type of inspection and repair action that is undertaken at a given time. If the inspection and repair actions on the pipeline are predominately characterized by major repairs, the probability of failure is expected to be lower than that with minor repair action.

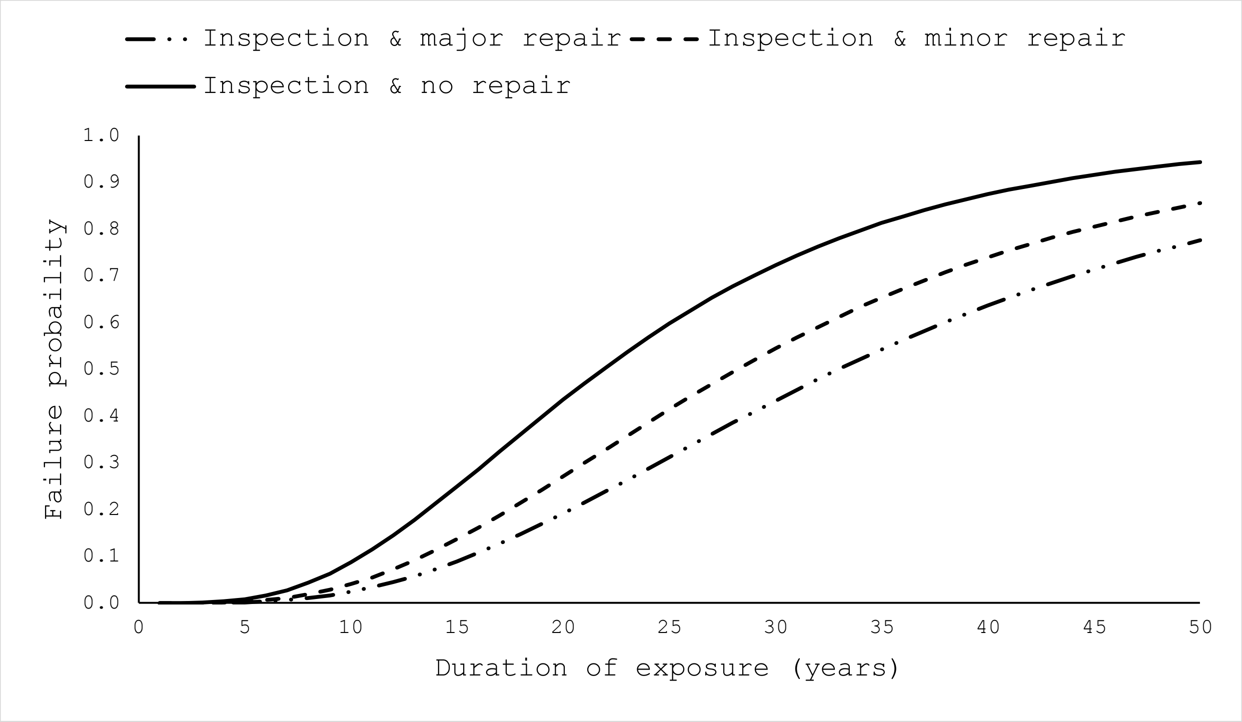


Figure 7: Failure probability of corroded pipeline managed with different inspection and repair options

Despite the lower failure probability expected with the inspection and major repair action, the cost of managing the pipeline integrity under this scenario is more than that for the other two options (see Figure 8).

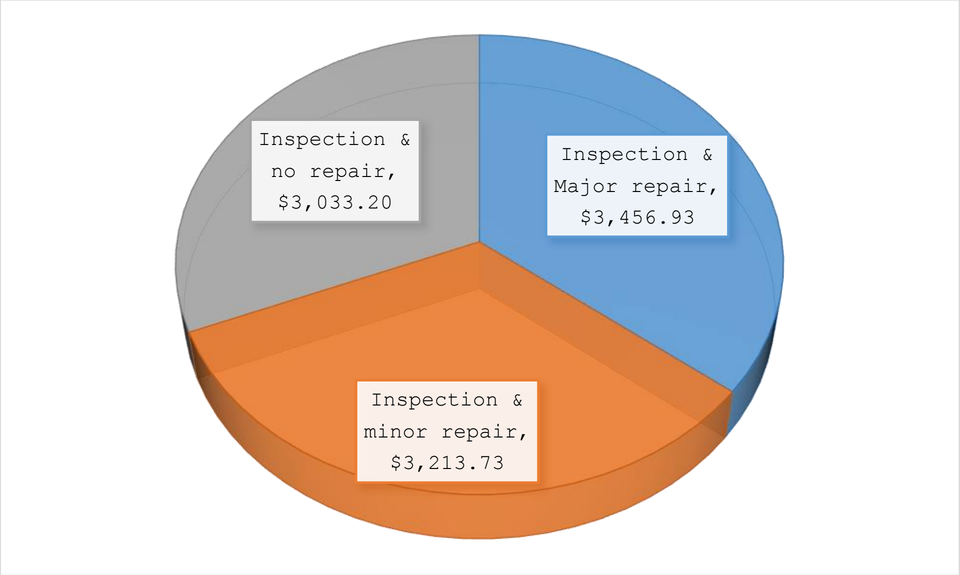


Figure 8: Long run inspection and repair cost (per km-yr.) for different inspection and repair options for maintaining a corroded pipeline

With increase in the number of defects on the pipelines, the cost of inspection and repair actions increases across the board for both major and minor repairs but not with spots that need no repair action after ILI inspection as shown in Figure 9. If the number of defect spots in a pipeline needing major or minor repairs increases, the cost of repairs increases as shown in the figure. Although there may be isolated cases of this sort of occurrence, however, the company could always make a decision to change a substantial section of a pipeline that has deteriorated due to corrosion, when it is no longer economical to repair.

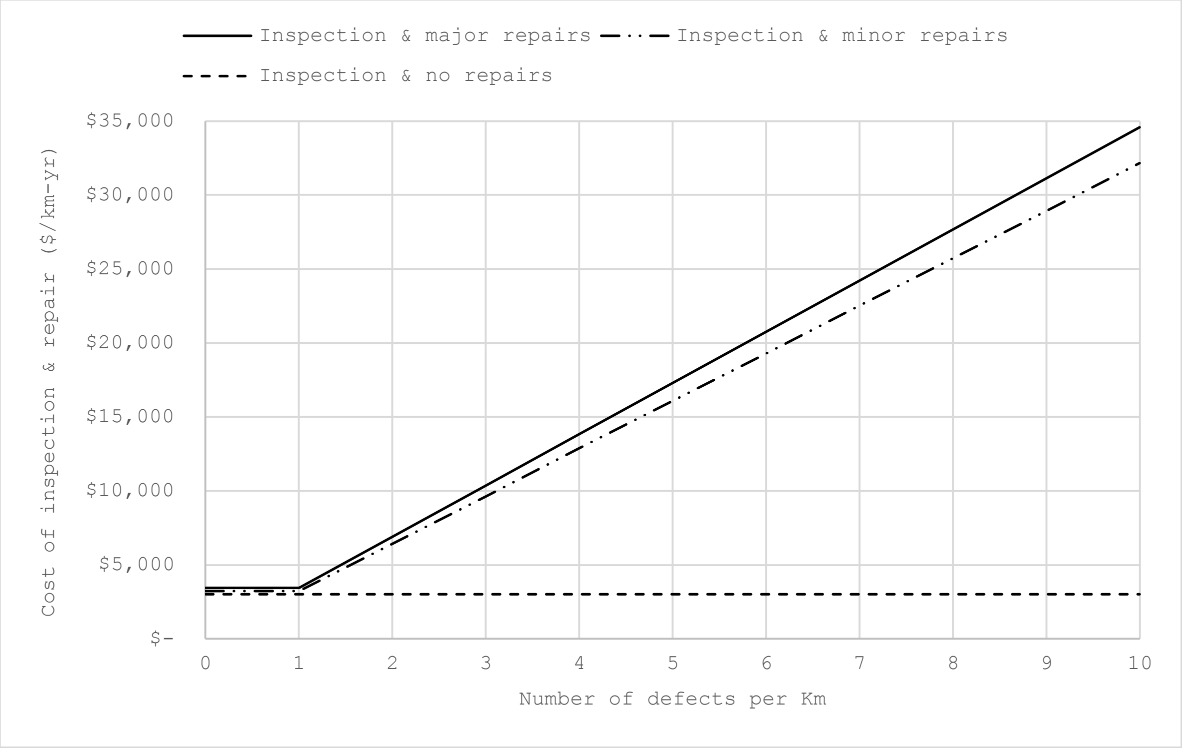


Figure 9: Variation of cost of inspection and repairs for number of corrosion defects per kilometre

Over a finite planning horizon, the inspection and repair cost per km of the corroded pipeline is also expected to have inspection and major repair having the highest value, inspection and minor repair having the second highest value whilst inspection and no repair will have the least value. This case is shown in Figure 10.

6.3 Future cost of inspection and repair

Managing the integrity of corroded pipelines based on only one of the inspection and repairs action stipulated in this research may not be most economical for stakeholders, since there is need to maintain both integrity and optimize cost at all times. Hence, a future inspection and repair option for the corrosion defect depths involves the combination of the three inspections and repair options. This is extremely necessary for cost optimization and risk minimization given the fact that the defect rates at the defect spots of the pipelines are always varying. In order to apply the strategy described in section 5.6 to determine the optimal future cost of inspection and repair of the pipeline, it was assumed that-

I. The corrosion defect depth was growing linearly and hence the future corrosion wastage was determined as a linear model in consideration of the previous corrosion wastage rate at each of the defect spots.

II. The corrosion defect depths grew randomly but based on discrete corrosion wastage rates. This implies that the corrosion defect depths are expected to grow at random based on the prevalent corrosion wastage rates at the corrosion defect spots on the pipeline. Hence, a spot having small corrosion growth rate may grow more rapidly than those that grew rapidly prior to the ILI of the pipeline and vis-versa.

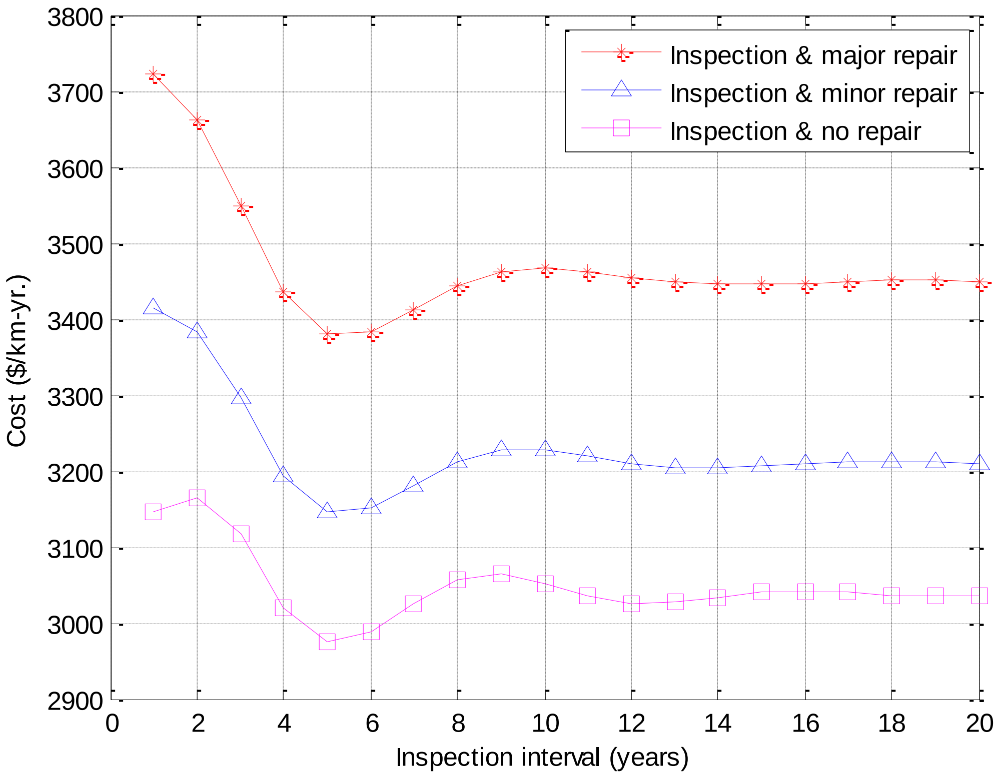


Figure 10: Variation of the cost of managing pipeline integrity based on the inspection and repair actions over a finite planning horizon.

The variation of the inspection and repair cost over a future inspection time of 25 years is shown in Figure 11.

The cumulative cost of inspection and repair of the pipeline based on linear model and random corrosion defect depth growth using Monte Carlo simulation did not show much distinction after 25 years inspection and repairs. The inspection and repair action that was based on random corrosion defect depth growth was approximately 2% higher than that determined on the basis of linear modelling. This implies that the linear modelling approach could be a potential cost saving approach in comparison to the random corrosion wastage growth. Despite this result, it will be appropriate to compare the future corrosion defect depths growth obtained with this process with that obtained from ILI prior to deciding on the appropriate repair actions.

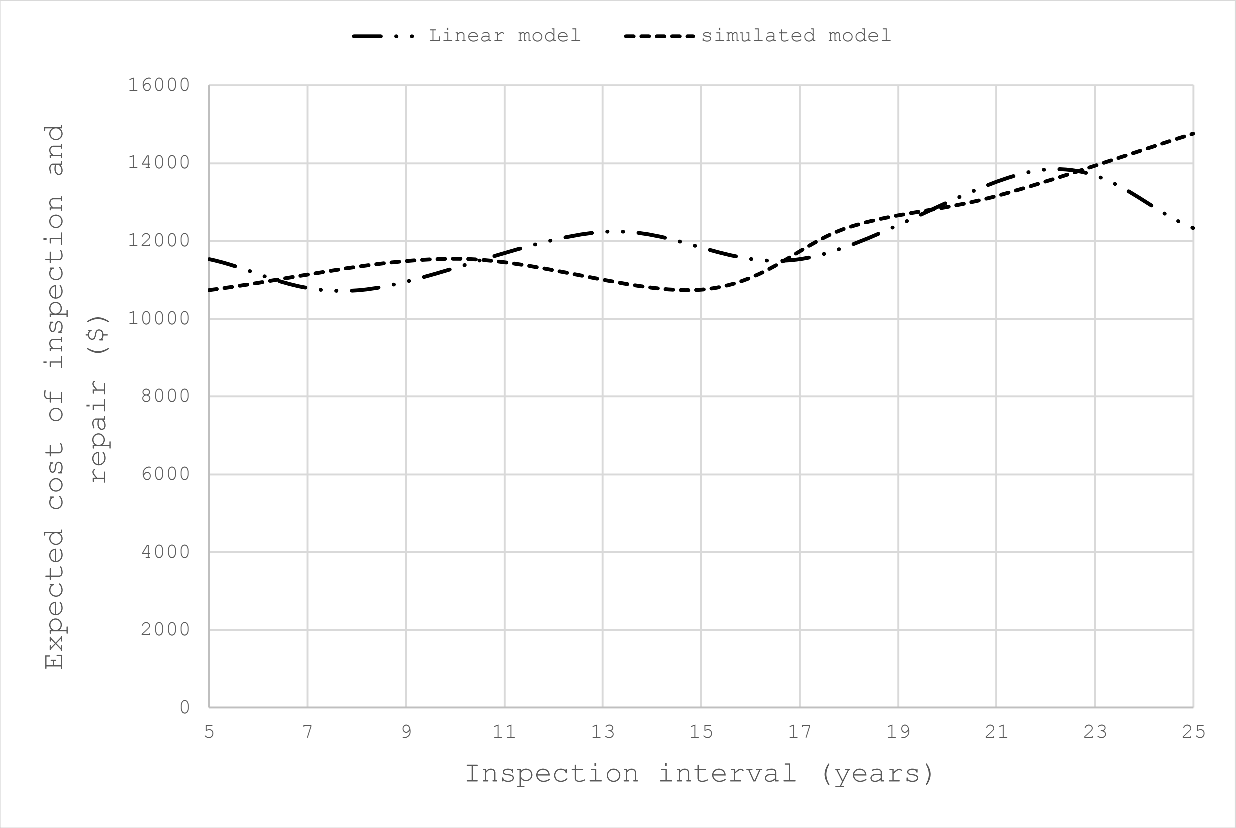


Figure 11: Cost of inspection and repair for different linear predicted and random growth of corrosion defect depth

7.0 Conclusions

Managing of an internally corroded pipeline is a complicated task that involves the calculation of the Remaining Useful Life (RUL) of the pipeline based on the retained pipe-wall thickness at the time of inspection. The retained pipe-wall thickness of the pipeline as a measure of the RUL was used to classify pipeline lifecycle phases at introduction, maturity, ageing, terminal, failure or leakage. The transition probabilities between these lifecycle phases based on five state Markov decision process were determined using the corrosion wastage rates.

The holding time of different inspection and repair actions over a finite planning horizon was determined for the corroded pipeline whereas the expected failure probability of the corroded pipeline over a given time of exposure of the pipeline to corrosion was determined for the inspection and repair actions considered. The research also described a technique for evaluating future inspection and repair cost of corroded pipelines by relaying on the corrosion defect depth information of previous ILI.

The results obtained from this research proves that Markov modelling and Monte Carlo simulation can be utilized for modelling stochastic behaviour of corrosion defect depths. Hence, the ease of determining failure probability and types of repair that is appropriate at a given time in the lifecycle duration of a pipeline and the associated future cost of inspection and repairs. This means that the integrity of corroded pipelines can be maintained whilst optimizing the expected cost of future inspection and repairs of internally corroded pipelines.

References

[1]. Fang H, Brown B, Nescaronicacute S, Effects of sodium chloride concentration on mild steel corrosion in slightly sour environments, Corrosion 2011, 67(1): 015001-1-015001-12.

[2]. Nesic S, Key Issues Related to Modelling of Internal Corrosion of Oil and Gas Pipelines – a Review, Corrosion Science 2007, 49: 4308-4338.

[3]. Singer M, Brown B, Camacho A, Nesic S, Combined effect of carbon dioxide, hydrogen sulfide, and acetic acid on bottom-of-the-line corrosion, Corrosion 2011,67(1): 015004-1-015004-16

[4]. Ossai CI, Pipeline Corrosion Prediction and Reliability Analysis: A Systematic Approach with Monte Carlo Simulation and Degradation Models, International Journal of Scientific & Technology Research 2013,2(3)

[5]. Ma B, Shuai J, Liu D, Xu K, Assessment on Failure Pressure of High Strength Pipeline with Corrosion Defects, Engineering Failure Analysis 2013, 32: 209-19.

[6]. Hu X, Barker R, Neville A, Gnanavelu A, Case study on erosion–corrosion degradation of pipework located on an offshore oil and gas Facility, Wear 2011, 271:1295– 1301

[7]. CAPP, Best Management Practices: Mitigation of Internal Corrosion in Oil Effluent Pipeline Systems, 2009, Calgary Canada, 2009, Retrieved from http://www.capp.ca/getdoc.aspx?DocId=155641&DT=PDF on [19/6/14].

[8]. Review of corrosion management for offshore oil and gas processing, HSE offshore technology report 2001/044, 200, Retrieved from http://www.hse.gov.uk/research/otopdf/2001/oto01044.pdf on [22/6/14]

[9]. Alberta Energy regulator (AER), Report 2013 - B: Pipeline performance in Alberta, 1990–2012, (2013), Retrieved from http://www.aer.ca/documents/reports/R2013-B.pdf [2/12/14].

[10]. Ahammed M, Prediction of remaining strength of corroded pressurised pipelines, International Journal of Pressure Vessels and Piping 1997, 71(3): 213-217.

[11]. Sahraoui Y, Khelif R, Chateauneuf A, Maintenance planning under imperfect inspections of corroded pipelines." International Journal of Pressure Vessels and Piping 2013, 104(0): 76-82.

[12]. Hu J, Tian Y, Teng H, Yu L, Zheng M ,The Probabilistic Life Time Prediction Model of Oil Pipeline Due to Local Corrosion Crack, Theoretical and Applied Fracture Mechanics 2014, 70: 10-18.

[13]. Dawotola AW, van Gelder PHAJM, Charima JJ, Vrijling JK, Estimation of failure rates of crude product pipelines, Applications of Statistics and Probability in Civil Engineering – Faber, Köhler & Nishijima (eds) Taylor & Francis Group, London, 2011

[14]. Gomes WJS, Beck AT, Haukaas T, Optimal Inspection planning for onshore pipelines subjected to external corrosion, Reliability Engineering and system safety 2013, 118: 18-27.

[15]. Wang N, Zarghamee M, Evaluating Fitness-for-Service of Corroded Metal Pipelines: Structural Reliability Bases, J. Pipeline Syst. Eng. Pract. 2014, 5(1): 04013012

[16]. Hasan S, Khan F, Kenny S, Probability Assessment of Burst Limit State Due to Internal Corrosion, International Journal of Pressure Vessels and Piping 2012: 48-58.

[17]. Zhou W , System reliability of corroding pipeline, international journal of pressure vessels and piping 2010, 87: 587-595.

[18]. Maes MA, Faber MH, Dann, MR, Hierarchical modeling of pipeline defect growth subject to ILI uncertainty, ASME 2009 28th International Conference on Ocean, Offshore and Arctic Engineering. American Society of Mechanical Engineers, 2009.

[19]. Ossai CI, Boswell B, Davies IJ, Pipeline failures in corrosive environments – A conceptual analysis of trends and effects, Engineering Failure Analysis, 2015, 53: 36-58.

[20]. Sheils E, O'Connor A, Schoefs F, Breysse D, Investigation of the Effect of the Quality of Inspection Techniques on the Optimal Inspection Interval for Structures, Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and performance, 2012, 8:6:557-568.Zhang, X, Gao, H, Road Maintenance Optimization Through a Discrete-Time Semi-Markov Decision Process, Reliability Engineering and System Safety, 2012, 103: 110–119.

[21]. Ana EV, Bauwens, W, Modeling the structural deterioration of urban drainage pipes: the state-of-the-art in statistical methods, Urban Water Journal, 2010, 7(1): 47-59, DOI: 10.1080/15730620903447597

[22]. Zhang, X, Gao, H, Road Maintenance Optimization Through a Discrete-Time Semi-Markov Decision Process, Reliability Engineering and System Safety, 2012, 103: 110–119.

[23]. Valor A, Caleyo F, Alfonso L, Velazquez JC , Hallen JM, Markov Chain Models for the Stochastic Modeling of Pitting Corrosion, Mathematical Problems in Engineering 2013, Article ID 108386

[24]. Sinha, SK, Mckim, RA, Probabilistic Based Integrated Pipeline Management System, Tunnelling and underground space technology, 2007, 22: 543-552.

[25]. Lounis, Z, Probabilistic modeling of chloride contamination and corrosion of concrete bridge structures. In Uncertainty Modeling and Analysis, 2003. ISUMA 2003. Fourth International Symposium on (pp. 447-451). IEEE

[26]. Gomes WJS, Beck AT, Optimal Inspection of Onshore Pipelines Subject to External Corrosion. *Chemical Engineering transactions*, 2013, *33:* 839-834.

[27]. ASME, 1991, Manual for determining the remaining strength of corroded pipelines. American Society of Mechanical Engineers, B31G, New York.

[28]. Cekyay B, Ozekici S, Optimal Maintenance of Systems with Markovian Mission and Deterioration, European journal of Operation Research 2012, 219: 123-133.

[29]. White CC III, White DJ, Markov Decision Process, European Journal of Operational Research 1989, 39:1-16.

[30]. Stephens M, Nessim M, A comprehensive approach to corrosion management based on structural reliability methods. In 2006 International Pipeline Conference (pp. 695-704). American Society of Mechanical Engineers.

[31]. Papavinasam S, Doiron A, Revie RW, Model to Predict Internal Pitting Corrosion of Oil and Gas Pipelines. Corrosion, 2010, 66(3): 035006-035006-11.

[32]. Cole IS, Corrigan P, Sim S, Birbilis N, Corrosion of pipelines used for CO2 transport in CCS: Is it a real problem? *International Journal of Greenhouse Gas Control*, 2011, *5*(4): 749-756.

[33]. Melchers RE, Extreme value statistics and long-term marine pitting corrosion of steel, Probabilistic Engineering Mechanics 2008, 23(4):482-488.

[34]. Nessim M, Dawson J, Mora R, Hassanein S, Obtaining corrosion growth rates from repeat in-line inspection runs and dealing with the measurement uncertainties. In 2008 7th International Pipeline Conference (pp. 593-600). American Society of Mechanical Engineers

[35]. Caleyo F, Velázquez JC, Valor A, Hallen JM, Markov chain modelling of pitting corrosion in underground pipelines, Corrosion Science 2009, 51:197–2207.

[36]. Kulkarni VG, Introduction to Modeling and Analysis of Stochastic Systems, Springer Texts in Statistics, 2011, DOI 10.1007/978-1-4419-1772-0 2.

[37]. Feldman RM, Valdezffores C, Applied probability and stochastic processes 2nd edition. Springer, New York, 2010, ISBN: 978-3-642-05155-5.

[38]. Kallenberg L, Makov decision processes, 2011 , Retrieved from: http://www.math.leidenuniv.nl/~kallenberg/Lecture-notes-MDP.pdf 2/12/2014

[39]. Plant Ageing, Management of Equipment Containing Hazardous Fluids or Pressure. HSE Research Report RR509, HSE Books, 2006.

[40]. Managing Ageing Plants-Summary Guide. HSE Research Report RR823, HSE Books, 2010.

[41]. Ossai CI, Advances in asset management techniques: An overview of corrosion mechanisms and mitigation strategies for oil and gas pipelines, ISRN Corrosion 2012, Article ID 570143

[42]. Abdallah M, Guar gum as corrosion inhibitor for carbon steel in sulfuric acid solutions, Portugaliae Electrochimica Acta, 2004, 22: 161-175.

[43]. Valcarce MB, Vázquez M, Carbon steel passivity examined in solutions with a low degree of carbonation: The effect of chloride and nitrite ions. Materials Chemistry and Physics, 2009, 115(1): 313-321.

[44]. Biomorgi J, Hernández S, Marín J, Rodriguez E, Lara M, Viloria A, Internal corrosion studies in hydrocarbons production pipelines located at Venezuelan Northeastern. Chemical Engineering Research and Design, 2012, 90: 1159-1167

[45]. HSE. 2001. Review of corrosion management for offshore oil and gas processing, HSE offshore technology report 2001/044. Available from: <http://www.hse.gov.uk/research/otopdf/2001/oto01044.pdf>. [22/6/15]

[46]. Venkatesh CD, FARINHA PA, Corrosion Risk Assessment (CRA) in the oil and gas industry-An overview and its holistic approach, 2006, Available from: <http://members.iinet.net.au/~extrin/ConferencePapers/CAP04~Paper06.pdf>. [18/6/15].

[47]. Sastri VS, Perumareddi JR, Selection of corrosion inhibitors for use in sour media. *Corrosion*, 1994, *50*(6): 432-437.

[48]. Vega OE, Hallen JM, Villagomez A, Contreras A, Effect of Multiple Repairs in Girth Welds of Pipelines on the Mechanical Properties, Materials Characterization 2008, 59: 1498-507.

[49]. NACE standard RP0775, Preparation, installation, analysis and interpretation of corrosion coupons in oilfield operations, NACE international, Houston, TX. USA, 2005

[50]. Ossai CI, Boswell B, Davies IJ, Predictive Modelling of Internal Pitting Corrosion of Aged Non-Piggable Pipelines, *J. Electrochem. Soc.*, 2015, 162(6): C251-C259, doi: 10.1149/2.0701506jes

[51]. Rivas D, Caleyo F, Valor A, Hallen JM, Extreme value analysis applied to pitting corrosion experiments in low carbon steel: Comparison of block maxima and peak over threshold approaches, Corrosion Science 2008, 50: 193–3204.

[52]. Katano Y, Miyata K, Shimizu H, Isogai T, Predictive Model for Pit Growth on Underground Pipes, *Corrosion 2003,* 59(2): 155-161.

[53]. Bazan FAV, Beck T, Stochastic process corrosion growth models for pipeline reliability, Corrosion Science,2013, 74: 50-58.

[54]. Zhang S, Zhou W, System reliability of corroding pipelines considering stochastic process-based models for defect growth and internal pressure. International Journal of Pressure Vessels and Piping, 2013, 111-112: 120-130

[55]. Ossai CI, Boswell B, Davies IJ, Estimation of Internal Pit depth Growth and Reliability of Aged Oil and Gas Pipelines - A Monte Carlo simulation Approach, Corrosion: August 2015, Vol. 71, No. 8, pp. 977-99, doi: http://dx.doi.org/10.5006/1543

[56]. Hokstad P, Frovig AT, The modelling of degraded and critical failures for components with dormant Failures. Reliability Engineering and System Safety, 1996; 51: 189–199.

[57]. Bello D, Riano G, Linear programming solvers for markov decision processes. In *IEEE Systems and Information Engineering Design Symposium* 2006: 90-95.

[58]. Zhang S, Zhou W, Cost-based optimal maintenance decisions for corroding natural gas pipelines based on stochastic degradation models, *Engineering Structures* 2014,74: 74-85.

[59]. American Gas Association, Summary of Costs and Factors Impacting, In-Line Inspection, Direct Assessment, Pressure Testing and Pipeline Replacements For Natural Gas

Transmission Pipelines, 2011, Retrieved from <http://www.aga.org/our-issues/safety/pipleinesafety/Technicalreports/Documents/ILI%20DA%20Hydro%20Replacement%20Cost%20and%20Factors%20Summary%20Final%2004-04-11.pdf>. [2/12/14].

[60]. Thompson, N. G., Appendix E- Gas and Liquid Transmission Pipelines Full Report - dnV, Retrieved from <http://www.dnvusa.com/Binaries/gasliquid_tcm153-378807.pdf>. [2/6/15].

[61]. Thompson, N. G., Appendix J- Gas distribution, Retrieved from: <http://www.dnvusa.com/Binaries/gas_tcm153-339949.pdf>. [16/6/15].

[62]. Mohd MH, Paik JK, Investigation of the corrosion progress characteristics of offshore subsea oil well tubes, Corrosion Science, 2013, 67: 130-141.