Pipeline Corrosion Prediction And Reliability Analysis: A Systematic Approach With Monte Carlo Simulation And Degradation Models

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Abstract: - In this research, Monte Carlo Simulation and degradation models were used to predict the corrosion rate and reliability of oil and gas pipelines. Discrete random numbers simulated from historic data were used to predict the corrosion rate using Brownian Random walk while the mean time for failure (MTFF) was estimated with the degradation models. The Survivor probability of the pipelines was determined with weibull analysis using the MTFF. The result of the study shows that the degradation models and Monte Carlo simulation can predict the corrosion rate of the pipelines to an accuracy of between 83.3-98.6% and 85.2- 97% respectively.

Index Terms: - *corrosion prediction, reliability analysis, degradation models, Monte Carlo simulation, mean time for failure (MTFF), survivor probability*.

1 INTRODUCTION

Estimation of pipeline corrosion is fundamental to the analysis of pipeline reliability. The corrosion of pipelines can be described as a systematic degradation of the pipeline wall due to the actions of operating parameters on the pipeline material. Since corrosion is a fundamental cause of pipeline failures in oil and gas industries [1], [2],[3], the minimization will inevitably result in the increased productivity. To prioritize inspection according to the permissible risk level involves the understanding of the consequences of failure of a component on a system [4]. This requires the analysis of the system according to stipulated standards in order to predict the remaining life. For effective monitoring of pipeline reliability and remaining life prediction therefore, corrosion risk assessment is necessary. In order to manage corrosion risks, monitoring and inspection program will be incorporated into the overall activity schedule of an organization. The probability of failure is estimated based on the type of corrosion damage expected to occur while the consequences of failure are measured against the impact of such a failure evaluated against a number of criteria. The criteria could include potential hazards to environment, risks associated with safety and integrity, or risk due to corrosion or inadequate corrosion mitigation procedure [5]. Pipeline used in oil and gas production fail due to factors that are operationally, structurally and environmentally induced. The operational factors are associated with the components of the fluid flowing through while the environmental factors deal with the electrochemical and mechanical interactions of the pipeline material and the immediate surroundings.

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The arrangement of the microstructure and composition of the alloying elements essentially determine how the structural makeup of the pipeline resists corrosion. The impact of lateral and axial stresses on the reliability of pipelines was investigated by some authors [6] who concluded that stress contributes to pipeline failure especially for underground pipelines. Flow assisted corrosion (FAC) have resulted in reduced mechanical strength of pipelines and stress corrosion cracking. Though many methods exists for the measuring of the strength of oil and gas pipelines like ASME B31G and RSTRENG methods, SHELL 92,FORM and the recent Linepipe Corrosion (LPC) method, as presented in BS7910[7],[8],[9]. Experience has shown that older pipelines are not as tough as the new ones hence making test with most of these methods speculative [8]. To minimize downtime and its impacts on production facilities requires an integrated approach that provides the results that experts require to make timely decision about a facility [10]. In the case of pipeline failure, different techniques are necessary for estimating the mean time for failure in a bid to enhance informed decision about in-service inspection times and procedures. Predicting the corrosion and failure rates is done by using probabilistic approach through the use of internal corrosion direct assessment(ICDA) ,Monte Carlo simulation, first order reliability method (FORM), PIGS, ER-probes, H-probes, LPR etc.[3],[5],[7],[8],[10], The primary objective of this research is to predict pipeline corrosion rates using historic data vis-à-vis estimating the reliability of the pipeline over a period of time. This information is useful to pipeline corrosion experts who consistently plan corrosion mitigation activities through risk based inspections.

2.0 Monte Carlo Simulation and Corrosion Rate Prediction

Monte Carlo Simulation is a stochastic approach of predicting probability of the occurrence of an event by random number generation between 0 and 1. This simulation tool helps to develop a mathematical concept of complex real life system with a view to describing the behaviour of the system using probability of occurrence. To set up the simulation process involves the generation of randomly distributed random numbers between 0 and 1 using the mixed congruential method (MCM). The MCM generates sequence of U(0,1) random numbers denoted by $r_0, r_1, r_2 \ldots r_n$ according to the equation[1] below.

$$r_i = \frac{[(m * a * r_{i-1})(modulo(m))]}{m} --(1)$$

Where,

m is pre-specified positive integer known as modulus

a is pre-specified positive integer less than m known as the multiplier

c is non-negative integer less than m known as the increment.

The steps for the discrete random numbers generation using Monte Carlo simulation is shown in figure 1. The discrete random numbers generated is used to determine the previous value of corrosion rate (CR_p) used for yearly corrosion rate estimation from Brownian Random walk.

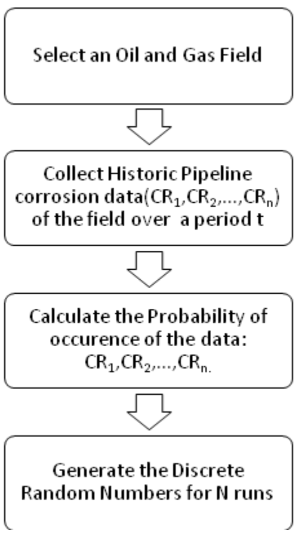


Figure 1: Framework for Monte Carlo Simulation of Discrete Random Numbers

2.1 <u>Estimating Corrosion Rate with Brownian Random Walk</u>

The corrosion rates in the pipeline is treated as a random number that follows an irregular time series path known as Brownian Walk. This is evidence from the trend of corrosion rate measured over a certain period in the field as shown from the case study used in this research. The volatility of this process is regulated by the Monte Carlo uniform distribution simulation [11].The Brownian random walk can be represented by equation (2)

$$\frac{\delta_{CR}}{CR_p} = e^{\mu\delta T + \sigma\varepsilon(\delta T)^{\frac{1}{2}}} -----------(2)$$

Where

δ_{CR}= Change in the corrosion rate from one year to another

CR_p= previous value of the corrosion rate (mm/yr).

μ= average value of the corrosion rate in each pipeline

σ = annualized volatility or standard deviation of the corrosion rate

δT= change in time(in years) from one step to another

Є= value from a probability distribution (determined with Monte Carlo Simulation)

$$\epsilon = \left(\sum_{i=1}^{n=12} PRNG\right) - 6 ------------(3)$$

Where PRNG= Portable random number generator.

The values of the average corrosion rate and standard deviation of the pipelines of the studied fields are calculated from the historic data. In this research, the previous value of the corrosion rate (CR_p) used in equation(2) is derived from Monte Carlo simulation process described in the previous section. The value is described as the annualized corrosion rate (ACR) of the pipelines in mm/yr. ACR is the highest occurring predicted discrete random number or the average of the predicted discrete random numbers contained in the 10^5 simulation runs carried out in the research. The Brownian random walk is used to predict yearly corrosion rate in mm/yr for the pipelines.

2.2 <u>Pipeline Corrosion wastage Estimation</u>

In order to predict the corrosion wastage of the pipeline, the ACR that will give the best estimate of the pipeline corrosion rate is determined. This is done by comparing the predicted corrosion rates with the historic data using root mean square error (RMSE). The RMSE is determined according to equation (4).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(CR_{pred} - CR_i)^2} ----(4)$$

Where

n= number of years of the historic corrosion data used for the prediction

CR_{pred}= Predicted Corrosion rate for ith year using equation(2)

CR_i= Measured field corrosion rate for ith year from historic data.

The ACR with the lower RMSE is used to predict the corrosion wastage of the pipelines over a stipulated time frame. The corrosion wastage represents the cumulative wall thickness loss of the pipeline at any time interval. The knowledge of the corrosion wastage aid in decisions concerning risks based inspection (RBI). If predicted corrosion rates using the best ACR (from equation (2)) for years 1, 2, ...,i are CR_1,CR_2, ...,CR_i, the corrosion wastage for the nth year (CR_n) is given by equation(5)

$$CR_n = CR_1 + CR_2 + \ldots + CR_i = \sum_{i=1}^{n} CR_i --(5)$$

The technique for predicting the pipeline corrosion wastage using Monte Carlo simulation is shown in Figure 2.

3.0 Degradation Analysis and Reliability Estimation

Degradation is a process of loss of integrity and function of a system due to ageing, operation and other factors which could include environmental and human factors. This phenomenon is common in pipelines, separators, turbines etc. According to research, process water with dissolved organic acid contributes to a high level of degradation of pipelines and other steel vessels in the oil and gas industries [12]. To predict the remaining life of the pipeline therefore requires the estimation of the rate of degradation vis-à-vis the reliability and the remaining life. Degradation is a continuous progression of wear and decay, so it can be modeled as a stochastic process. The measured degradation for i_{th} tested device (i=1,2,...,n) will consist of a vector of m_i measurements made at time points $ti_1,\ldots ti_{mi}$. The measured degradation time t can be modeled as the unknown degradation η(t) plus a measurement error term έ. At the m_i time point, the degradation measurement (Y_{ij}) of device i is given by equation (6)

$$Y_{ij} = \eta(t_{ij}) + \epsilon_{ij}, 1 < i \le n, i \le j \le m_i ----------(6)$$

The form of degradation (η) can be chosen to have a strict form or it can be more arbitrary. The forms of η used to determine the degradation of the pipeline is shown in equations (7)-(10)

1. Linear model: $CR = \alpha T_m + \beta --(7)$
2. Power model: $CR = \beta T_m{}^{\alpha} --- (8)$
3. Exponential Model : $CR = \beta e^{\alpha T_m} ---(9)$
4. Logarithmic model : $CR = \alpha \ln(T_m) + \beta --(10)$

Where

CR= degradation of pipeline due to corrosion (mm/yr)

T_m= Time, α & β are constants of model parameters

The above degradation model equations were used to estimate the time of failure of the pipeline. The time for failure is assumed to be reached when the corroded wall thickness is 45%-85% of the original wall thickness. The commuted time of failure (mean time for failure) was used for the life data analysis. The mean time for failure (MTFF) for the pipeline was established using the degradation model according to the relationship shown in equation (11)

$$MTFF = \begin{cases} \dfrac{p*ti - CR_{it} - \beta}{\alpha} & \text{for Linear Model} \\ \left[\dfrac{p*ti - CR_{it}}{\beta}\right]^{\frac{1}{\alpha}} & \text{for Powermodel} \\ \dfrac{\log\left[\dfrac{p*ti - CR_{it}}{\beta}\right]}{\alpha} & \text{for Exponential} \\ e^{\frac{p*ti - CR_{it} - \beta}{\alpha}} & \text{for Logarithmic} \end{cases} ------(11)$$

Where

ti = pipe wall thickness (mm)

p= percentage of corroded wall thickness (45%-85%)

CR_{it}= measured corrosion rates along the pipeline (mm/yr) at years (1, 2,..., n)

The determined MTFF is fitted to weibull analysis in order to establish the reliability of the pipeline over time thereby estimating the remaining life. The cumulative density function (CDF) for weibull distribution is given by equation (12)

$$F(t) = 1 - e^{-\left[\frac{t}{\gamma}\right]^{\theta}} --- (12)$$

Where

F(t) = cumulative density function of mean time for failure(the probability that a failure occurs before time t) γ & θ are scale and shape parameters respectively. The value of θ identifies the mode of failure rate. When θ <1, there is decreasing failure rate, θ=1, there is constant failure rate and when θ> 1, there is a wear out failure increasing over time .The scale factor parameter γ is the life at which 63.2% of the unit will fail. The framework for the degradation analysis for assessing the reliability of pipeline is shown in figure 3.

4.0 Prediction of Corrosion Rate - a Case Study

Extensive internal corrosion data measured at least twice in a year were collected over 8 years period from 11 different oil and gas fields in Nigeria OML 63 were used to test this model. These 114mm diameter pipeline were made of X52 grade steel material and carries oil and gas for about 700m to 14,000m. The corrosion rate was measured with inserted corrosion coupons and ER-probes. The ER-probes and corrosion coupons were used to determine the change in the corrosiveness of the pipelines due to changing operating parameters. The preparation, installation and analysis of the coupons and ER-probes were done according to NACE standard RR0775 and ASTM G.1[13],[14]

4.1 Modeling Studies

To set up the Monte Carlo simulation experiment for this research, historic corrosion rate of the studied 11 pipelines over 8 years were used. The Monte Carlo simulation was realized through 10^5 trial runs. Microsoft Excel 2007 was used for the simulation run. The simulation was achieved by using the inbuilt discrete random number generation function. This function uses the RAND() function to convert the cumulative density function into discrete uniform numbers. The discrete random numbers were generated from the set of historic corrosion rate measured for a particular pipeline. The COUNTIF function was used to determine the frequency of occurrence of the discrete random numbers which represent the simulated pipeline corrosion rate in mm/yr. The measured annual corrosion rate of the pipelines over the 8 year period is shown in Table1.

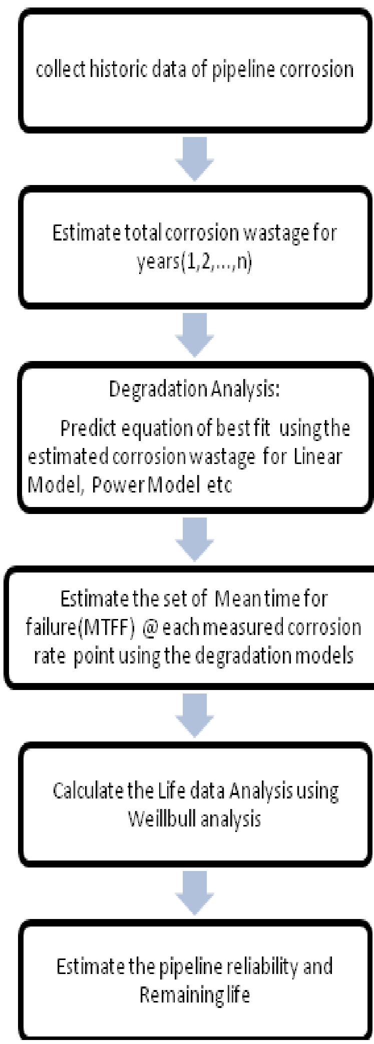
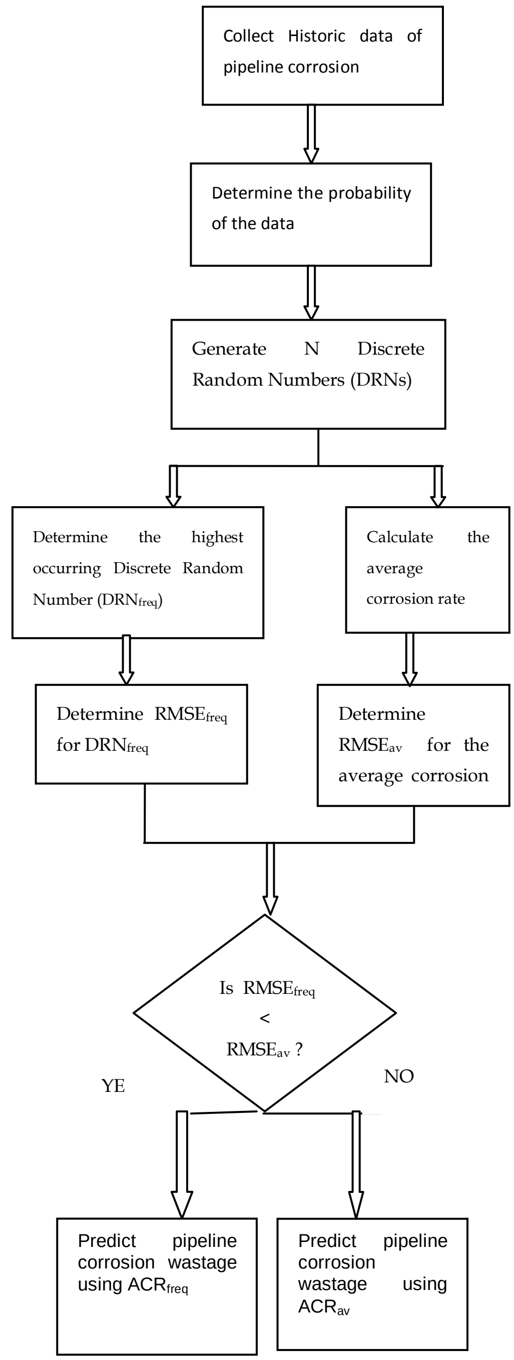


Figure 3: Degradation Analysis Framework for pipeline Reliability Estimate



$RMSE_{freq}$= Root mean square error determined with highest occurring discrete random num

$RMSE_{av}$= Root mean square error determined with the average of the discrete random numl

ACR_{av}= Annualized corrosion rate determined as the average of the discrete random numbe

ACR_{freq}= Annualized corrosion rate determined as the highest occurring discrete random nu

Figure2: Framework for pipeline corrosion wastage prediction using Monte Carlo

The values of the average corrosion rate and standard deviation of the pipelines of the studied fields are shown in Table 2. These values are assumed to follow a normal distribution. The information contained in this section is used for predicting the ACR rate for each of the pipelines. The application of the ACR in the relevant equations shown in the previous sections helped to determine the pipeline corrosion wastage on yearly basis

4.2 Degradation Analysis and Pipeline failure time estimation

Degradation analysis was performed on the historic data using linear and power models. Microsoft Excel 2007 analysis tool was used for the regression analysis and determination of the model constants that were used for predicting the best fit equations. These predicted equations of best fit were used for estimating the MTFF at each of the measured corrosion rate in the field by applying equation (11). For this study, the value of p in equation (11) is assumed to be 45% while the wall thickness of the pipeline is 8.56mm. The degradation equations and the regression coefficients are shown in Table 3.

Table 1:Cumulative Data of Pipeline Corrosion rate(mm/yr) from 2001- 2008

Field	***2001***	***2002***	***2003***	***2004***	***2005***	***2006***	***2007***	***2008***
S01	0.47	0.0415	0.095	0.025	0.07	0.055	0.045	0.06
S02	0.04	0.085	0.08	0.04	0.075	0.021	0.041	0.378
S03	0.045	0.19	0.17	0.265	0.26	0.123	0.019	0.223
S04	0.27	0.264	0.028	0.461	0.505	0.12	0.246	0.145
S05	0.146	0.235	0.204	0.081	0.124	0.077	0.054	0.046
S06	0.035	0.095	0.06	0.155	0.073	0.038	0.092	0.145
S07	0.043	0.037	0.069	0.074	0.103	0.088	0.065	0.026
S08	0.045	0.135	0.06	0.184	0.268	0.042	0.253	0.407
S09	0.06	0.155	0.051	0.26	0.022	0.086	0.277	0.199
S10	0.09	0.276	0.044	0.105	0.11	0.008	0.045	0.06
S11	0.05	0.08	0.014	0.049	0.078	0.1	0.023	0.097

Table 2: Mean and standard deviation of Measured field corrosion rate(mm/yr)

	Fields					
Parameters	S01	S02	S03	S04	S05	S06
μ(mean)	0.105	0.112	0.166	0.248	0.166	0.09
σ(std)	0.145	0.187	0.158	0.216	0.12	0.079
	Fields					
Parameters	S07	S08	S09	S10	S11	
μ(mean)	0.061	0.188	0.142	0.09	0.063	
σ(std)	0.05	0.187	0.146	0.095	0.053	

The estimated MTFF is used to estimate the survival probability of the pipelines and reliability of failures by applying equation (12).

Table 3: Degradation Model Equations and square of coefficient of regression

Field	Linear Model		Power Model	
	Equation	R^2	Equation	R^2
S01	$CR=5.5173x10^{-2}T-5.34x10^{-2}$	0.9920	$CR=4.7022x10^{-2}T^{1.084908}$	0.9887
S02	$8.106X10^{-2}T-6.251X10^{-2}$	0.8345	$4.5695X10^{-2}T^{1.220658}$	0.9558
S03	$1.80226X10^{-1}T-9.789x10^{-2}$	0.9733	$CR=6.211x10^{-2}T^{1.573307}$	0.9605
S04	$CR=2.73167X10^{-1}T-4.2X10^{-2}$	0.9675	$CR=2.50049X10^{-1}T^{1.025332}$	0.9634
S05	$CR=1.60893 x10^{-1}+1.12107 x10^{-1}T$	0.9267	$CR=1.81339X10^{-1}T^{0.880096}$	0.9477
S06	$CR=9.0185x10^{-2}T-5.374x10^{-2}$	0.9854	$CR=4.1837x10^{-2}T^{1.391633}$	0.9805
S07	$CR=7.2773x10^{-2}T-5.068x10^{-2}$	0.9853	$CR= 3.8769X10^{-2}T^{1.271936}$	0.9893
S08	$CR=1.81235x10^{-1}T-2.2881x10^{-1}$	0.9517	$CR=4.8669x10^{-2}T^{1.57655}$	0.9877
S09	$CR=1.42345x10^{-1}T-1.069x10^{-1}$	0.9643	$CR=6.8444x10^{-2}T^{1.328519}$	0.9769
S10	$CR=1.38571x10^{-1}+8.1845x10^{-2}T$	0.8913	$CR=1.30299x10^{-1}T^{0.916151}$	0.8830
S11	$CR=6.1404x10^{-2}T-2.104x10^{-2}$	0.9774	$CR=5.14x10^{-2}T^{1.054301}$	0.9777
T=time(years), CR= corrosion rate (mm/yr)				

To determine the relationship between the CDF and the parameters (θ,γ) in equation(12), a double logarithmic transformation was done in a bid to make it a linear equation in the form shown in equation(13).

$$\ln\ln\left[\frac{1}{1-F(t)}\right] = \theta\ln\gamma - \theta\ln t ------(13), where\ t = MTFF$$

To determine F(t) and i_{th} MTFF, the MTFF was ranked in ascending order and the median rank technique (equation

(14)) used to estimate the values [15].

$$Median\ Rank = \frac{i + 0.3}{n + 0.4} ---------(14)$$

$$where, i = ith\ \ MTFF\ \ of\ data, n = total\ number\ of\ data$$

By applying least square method, the values of θ and γ are calculated according to equation (15)-(18)

$$\bar{t} = \frac{1}{n}\sum_{i=1}^{n} \ln\left[\ln\left[\frac{1}{1 - \frac{i-0.3}{n+0.4}}\right]\right] ----------(15)$$

$$\overline{F(t)} = \frac{1}{n}\sum_{i=1}^{n} \ln t_i ------------(16), \quad where\ t = MTFF$$

$$\theta = \left[\frac{\left[n\sum_{i=1}^{n}(\ln t_i)\right]\left[\ln\left[\ln\frac{1}{1-\left(\frac{i-0.3}{n+0.4}\right)}\right]\right] - \left[\sum_{i=1}^{n}\ln\left[\ln\left(\frac{1}{1-\left(\frac{i-0.3}{n+0.4}\right)}\right)\right]\right]\left[\sum_{i=1}^{n}(\ln t_i)\right]}{\left[n\sum_{i=1}^{n}(\ln t_i)^2\right] - \left[\sum_{i=1}^{n}(\ln t_i)\right]^2}\right] ---(17)$$

$$\gamma = e^{\left(\overline{F(t)} - \frac{\bar{t}}{\theta}\right)} ----------(18)$$

The values of the shape and scale parameters for the weibull distribution analysis of the studied fields were calculate with Microsoft Excel 2007 as shown in table 4.

5.0 Results and Discussions.

After 100,000 simulations runs with Microsoft Excel 2007, a set of random discrete numbers representing the corrosion rates of the pipelines were achieved (Table 5). The result shows the frequency of occurrence of the corrosion rate and the average corrosion rate of the simulation runs.

Table 4: summary of Weibull analysis parameters and square of coefficient of Regression

Field	β	α	R^2
S01	10.07	65.88	0.80145
S02	8.06	44.24	0.812753
S03	4.40	19.21	0.716348
S04	18.54	13.61	0.935338
S05	29.99	32.00	0.949294
S06	3.76	37.85	0.672547
S07	5.31	48.84	0.665186
S08	6.24	19.83	0.787674
S09	7.16	25.07	0.77729
S10	16.67	42.96	0.873506
S11	41.35	61.39	0.889983

The shaded parts of the table represent the most occurring predictions of the discrete random numbers. Both the average corrosion rates and the highest occurring frequencies of the simulation runs are used as the annualized corrosion rate (ACR) for predicting the yearly corrosion rate and corrosion wastage. The ACR that has the least error is used for the prediction of the pipeline corrosion rate for the future. The root mean square error of the pipelines is shown in table 6. The result (Table 6) shows that the RMSE is lower for the average corrosion rate (CR_{av}) than the highest occurrence predicted random number (CR_{freq}). The RMSE of between 1.4%-16.74% for the degradation models was observed in this research. This value shows that the degradation models predicted the pipeline corrosion rate to an accuracy of between 83.26%- 98.6%. Since the average corrosion rate (CR_{av}) calculated from Monte Carlo simulation can predict the pipeline corrosion rate to an accuracy of between 85.18%- 96.98% according to Table 6, using it for future pipeline corrosion prediction will give the experts a good idea of the reliability of the pipelines for enhanced integrity management. The variation of the field measured and predicted (Monte Carlo simulation (CR_{pred}) and Degradation Model) corrosion rates for the pipelines are shown in figures 4a-4k. The value of R^2 ranges between 0.89-0.99 for the linear model and 0.88-0.99 for the power model (table3). This value shows that the degradation model has predicted the field corrosion of the pipelines to a high degree of accuracy and hence will be a vital tool for predicting the failure time of the pipelines. The weibull parameters in Table 4 were used to determine the survival probability and hence the reliability of the pipelines. The results of the survival probability of the pipelines are shown in Figures 5a-5k. The probability of failure of the pipelines over some years (10-40 years) was computed as shown in Table 7. The result shows that the pipelines expected life span is between 16 years to 77years.

Table 6: Root Mean Square Error (RMSE) of Predicted Models

Field	**Monte Carlo Simulation**		**Linear Model**	**Power Model**
	CR_{freq}	**CR_{av}**		
S01	2.11%	5.93%	4.94%	1.40%
S02	11.58%	9.42%	8.27%	7.96%
S03	14.43%	7.86%	6.85%	16.74%
S04	24.06%	14.82%	13.16%	13.77%
S05	11.85%	5.82%	7.22%	8.19%
S06	6.66%	3.81%	2.51%	4.60%
S07	3.96%	2.53%	2.03%	2.27%
S08	20.30%	10.84%	9.36%	6.17%
S09	42.54%	8.93%	6.27%	5.53%
S10	8.73%	6.98%	6.55%	8.25%
S11	5.88%	3.02%	2.14%	2.31%

The pipeline failure probability can be compared with the failure probability classification in Table 8 to determine the risk level that each pipeline faces at the stipulated years. This information is very vital in the formulation of risk based inspection (RBI) policy for the pipeline network of any oil and gas company. Based on Table 8, the failure probability is very low for all the pipelines after 10 years of operation but medium for pipeline S02. Pipelines S03 and S04 have very high corrosion rate for their entire lifecycle of 30 and 16 years respectively. This situation makes these pipelines to be top on the agenda of corrosion and integrity management. With pipelines S01, S02, S06, S07, S10 and S11 having a lifecycle of over 40years prior to failure, the RBI for them will not be as intensive as that of the other pipelines with less than 40 years lifecycle.

Table7: Expected Probability of pipeline failure at different years of inspection

Field	Year					
	10	15	20	25	30	40
S01	5.726x10^{-9}	3.392x10^{-7}	6.1408x10^{-6}	5.805x10^{-5}	3.638x10^{-4}	6.564x10^{-3}
S02	6.264x10^{-6}	1.643x10^{-4}	1.667x10^{-3}	1x10^{-2}	4.28x10^{-2}	3.588x10^{-1}
S03	5.6x10^{-2}	2.91x10^{-1}	7.045x10^{-1}	9.614x10^{-1}	-	-
S04	2.96x10^{-4}	9.95x10^{-1}	-	-	-	-
S05	6.66x10^{-16}	1.36x10^{-10}	7.58x10^{-7}	6.1x10^{-4}	1.34x10^{-1}	-
S06	6.651x10^{-3}	3.023x10^{-2}	8.66x10^{-2}	1.893x10^{-1}	3.409x10^{-1}	7.08x10^{-1}
S07	2.19x10^{-4}	1.88x10^{-3}	8.66x10^{-3}	2.81x10^{-2}	7.23x10^{-2}	2.92x10^{-1}
S08	1.39x10^{-2}	1.607x10^{-1}	6.519x10^{-1}	9.857x10^{-1}	-	-
S09	1.39x10^{-3}	2.45x10^{-2}	1.8x10^{-1}	6.25x10^{-1}	9.73x10^{-1}	-
S10	2.798x10^{-11}	2.41x10^{-8}	2.915x10^{-6}	1.2x10^{-4}	2.51x10^{-3}	2.62x10^{-1}
S11	0	0	0	1.11x10^{-16}	1.38x10^{-13}	2.026x10^{-8}

Table 8: Failure Probability Category[16]

Range	**Likelihood Category**	**Remark**
1×10^{-4} to 1.0	5	Very high
1×10^{-5} to 1×10^{-4}	4	High
1×10^{-6} to 1×10^{-5}	3	Medium
1×10^{-8} to 1×10^{-6}	2	Low
$< 1 \times 10^{-8}$	1	Very low

6.0 Conclusions

This paper used Monte Carlo simulation and degradation models to predict pipeline corrosion and establish the reliability of the pipeline over a certain period. The stipulated methodology for this study was tested with field data from 11 onshore oil and gas fields. The corrosion prediction involved discrete random numbers generation from historic data, estimation of yearly corrosion rate with Brownian random walk, prediction of the corrosion wastage (with linear and power models) and estimation of mean time for failure (MTFF) of the pipeline. The research showed that both the Monte Carlo Simulation and the degradation models can reasonable predict the pipeline corrosion rate while reliability information that was determined from weibull analysis of the MTFF could be a good guide for risk based inspection (RBI).

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Fig 4a:Predicted and field corrosion rate for S01 pipeline

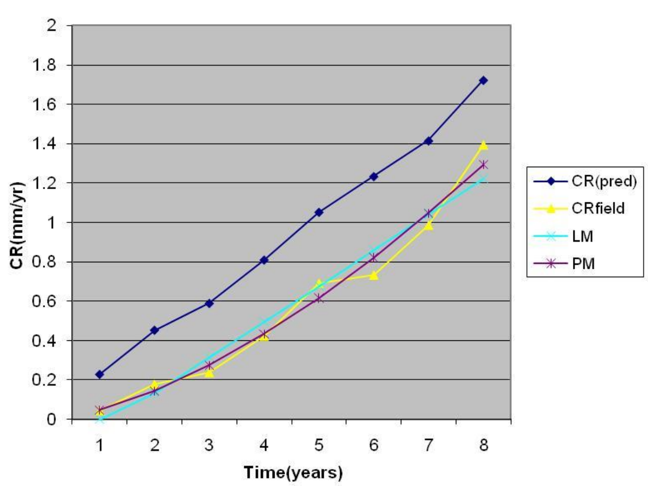


Fig 4b: predicted and field data of corrosion rate in S02 pipeline

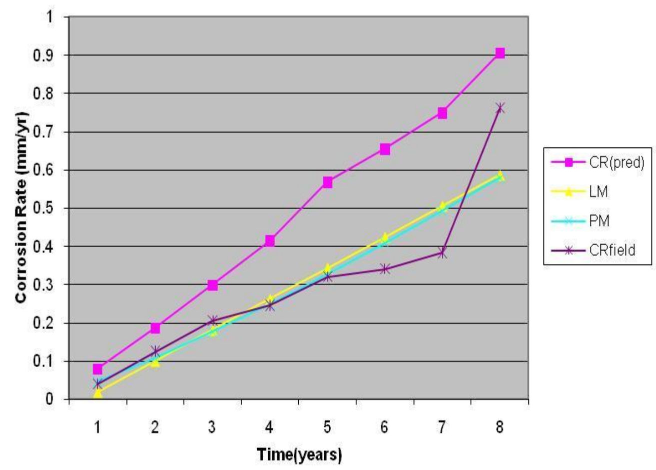


Fig 4c: Predicted and Field Corrosion rate of S03 Pipeline

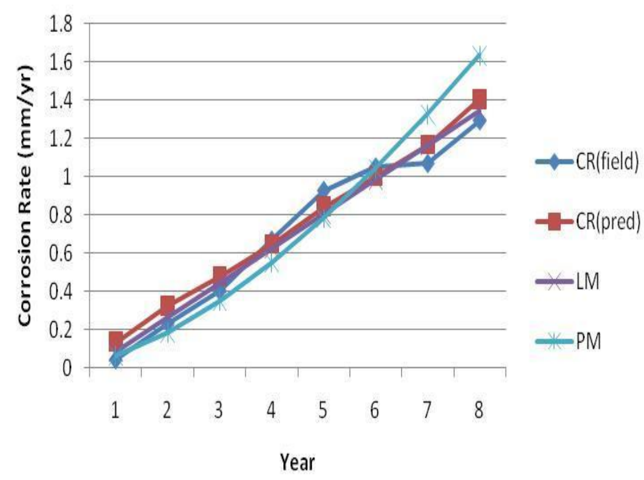
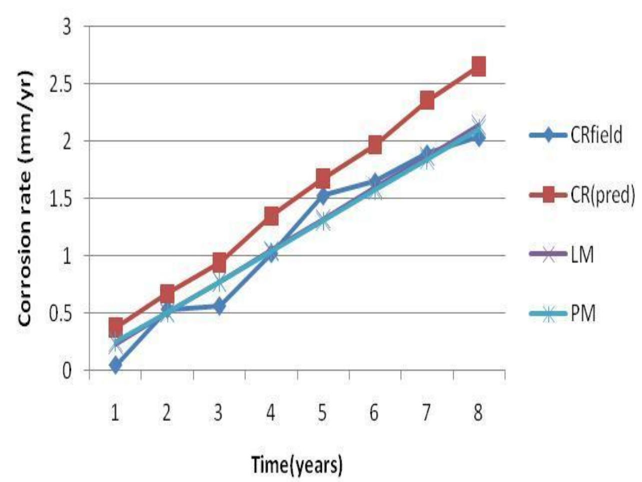


Fig 4d: Predicted and Field Corrosion Rate of S04 pipeline



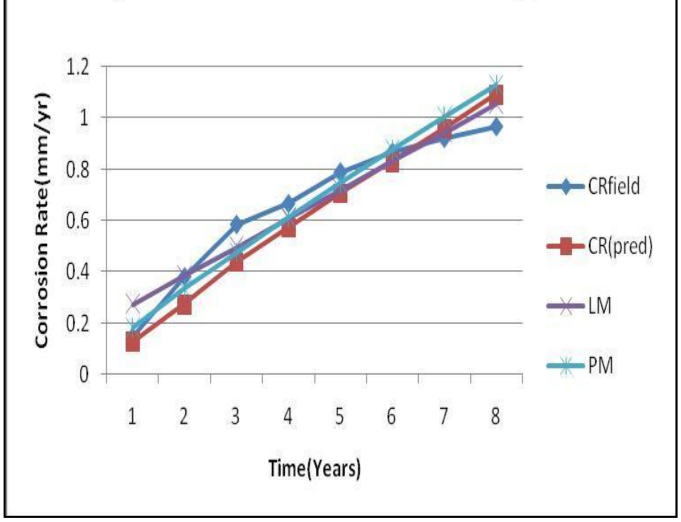


Fig 4e: Predicted and Field Corrosion Rate of S05 pipeline

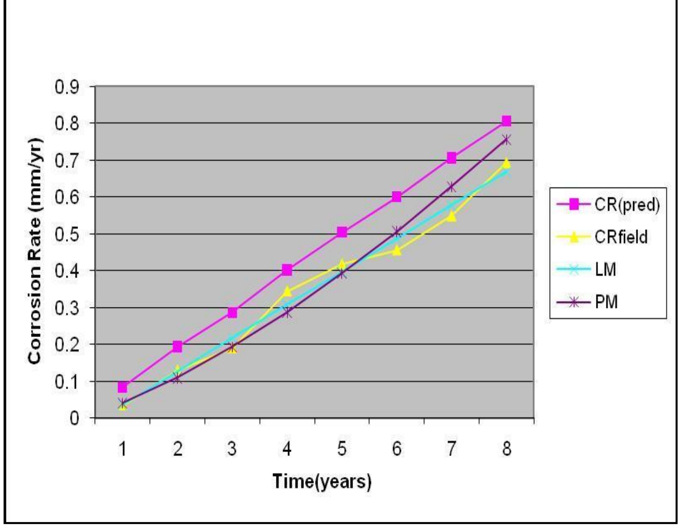


Fig 4f:Predicted and field corrosion rate for S06 pipeline

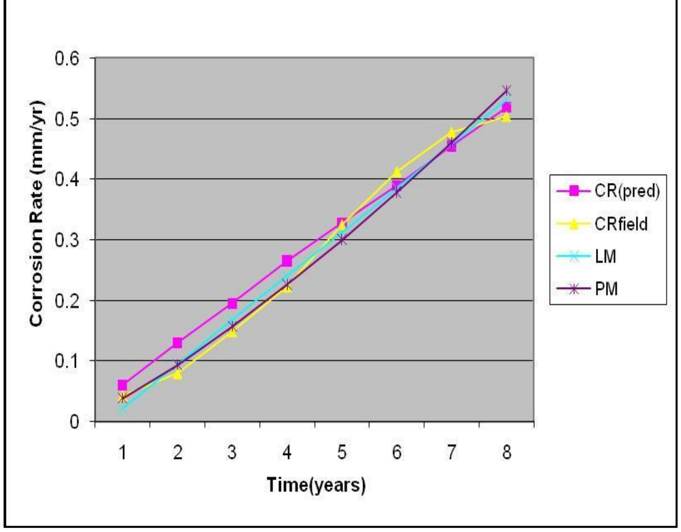


Fig 4g:Prdicted and Field corrosion rate for S07 pipeline

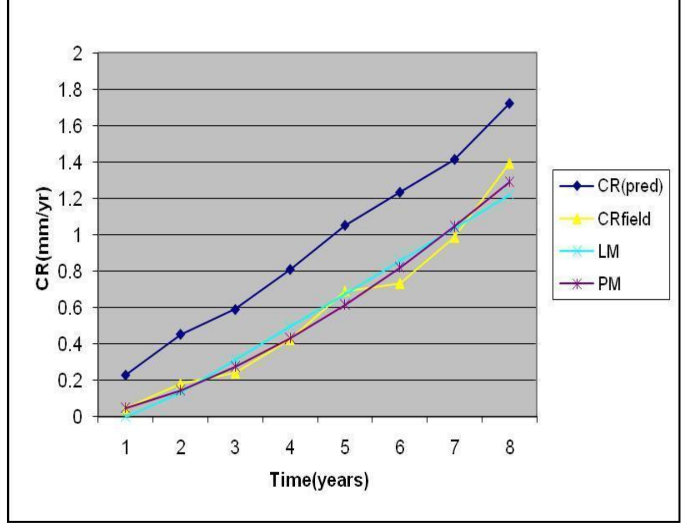


Fig4h:Predicted and field corrosion rate for S08 pipeline

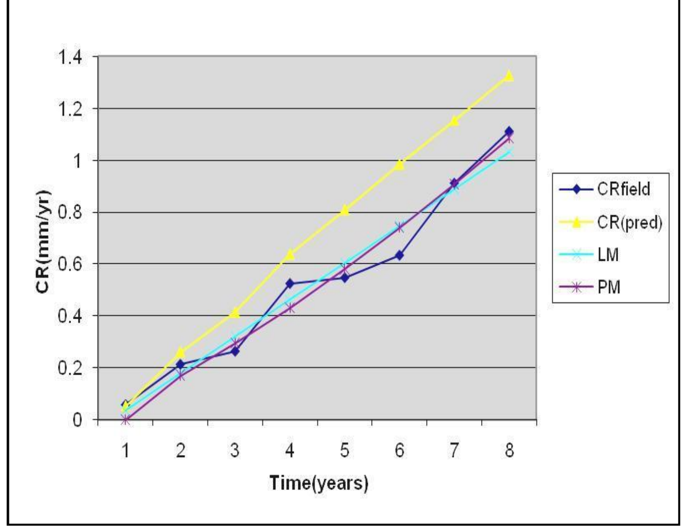


Fig 4i:Predicted and Field corrosion rate of S09 pipeline

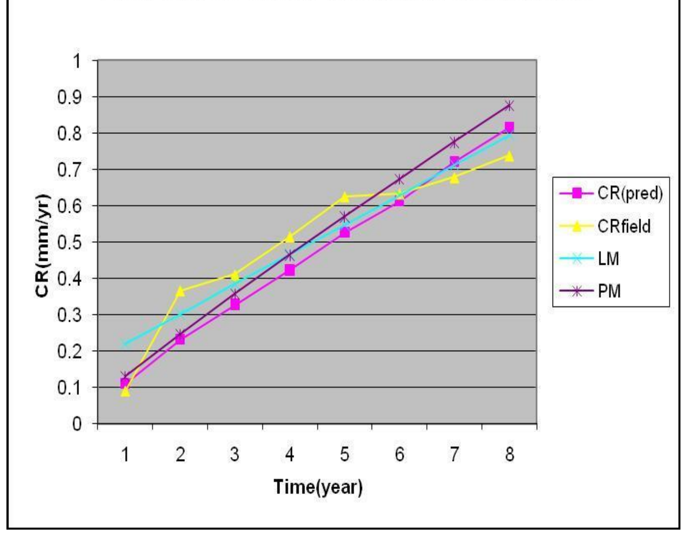


Fig 4j: predicted and field corrosion rate for S10 pipeline

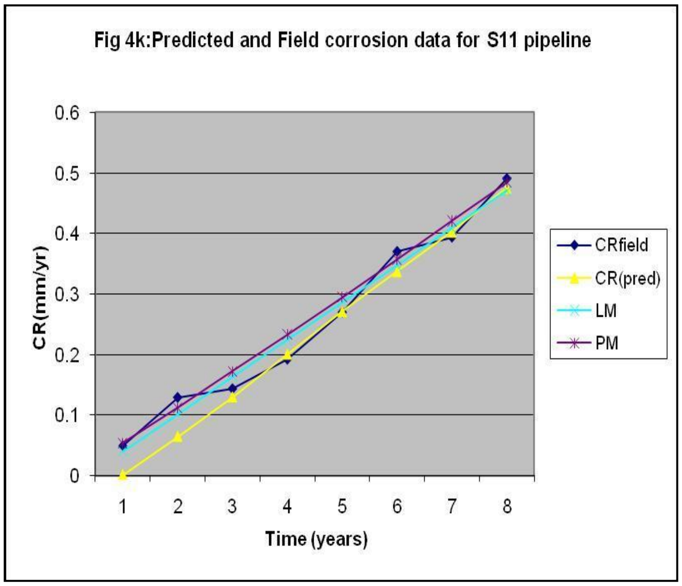


Fig 4k:Predicted and Field corrosion data for S11 pipeline

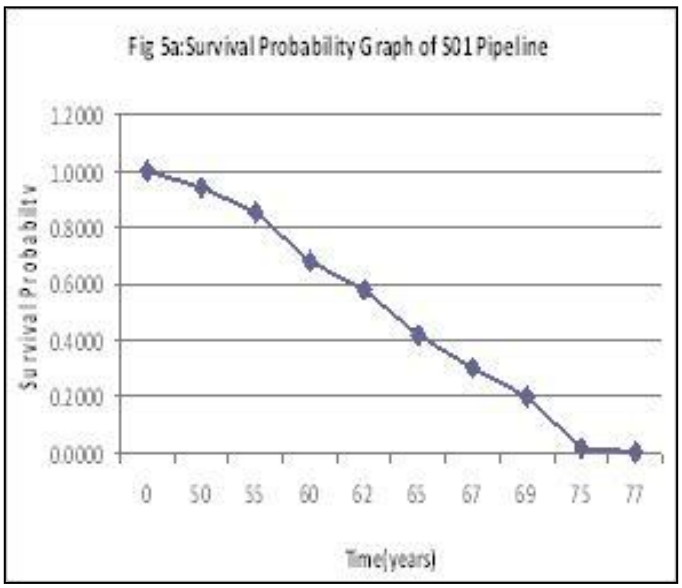


Fig 5a:Survival Probability Graph of S01 Pipeline

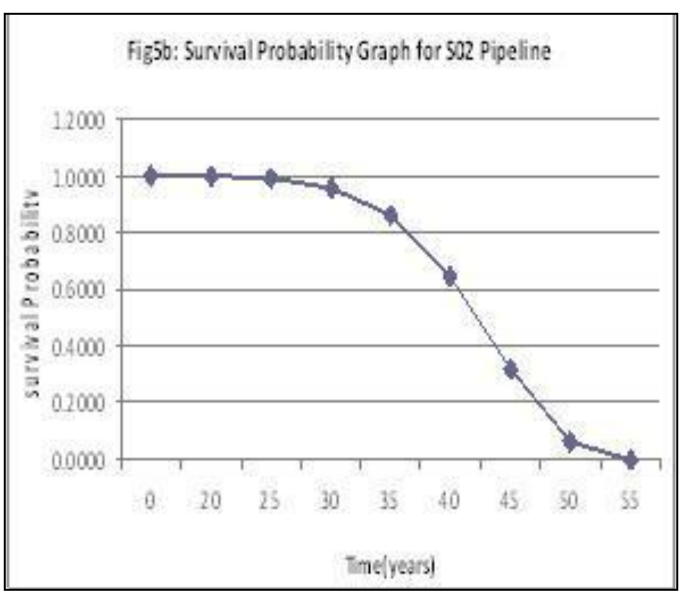


Fig5b: Survival Probability Graph for S02 Pipeline

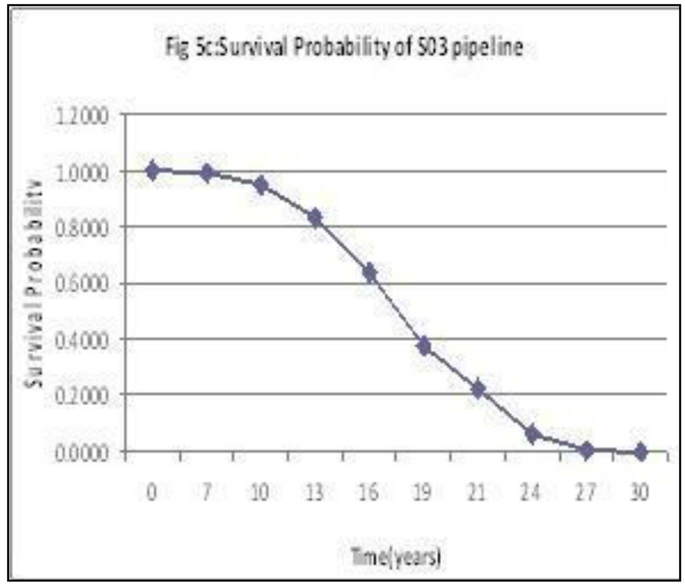


Fig 5c:Survival Probability of S03 pipeline

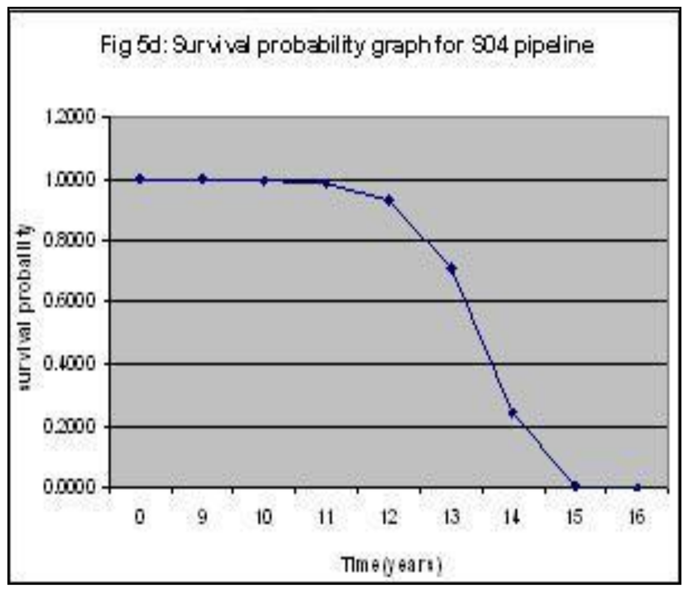


Fig 5d: Survival probability graph for S04 pipeline

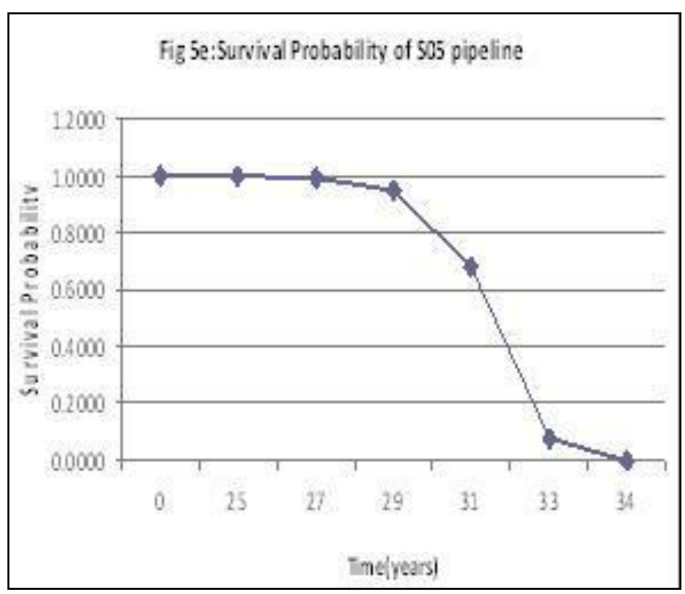


Fig 5e:Survival Probability of S05 pipeline

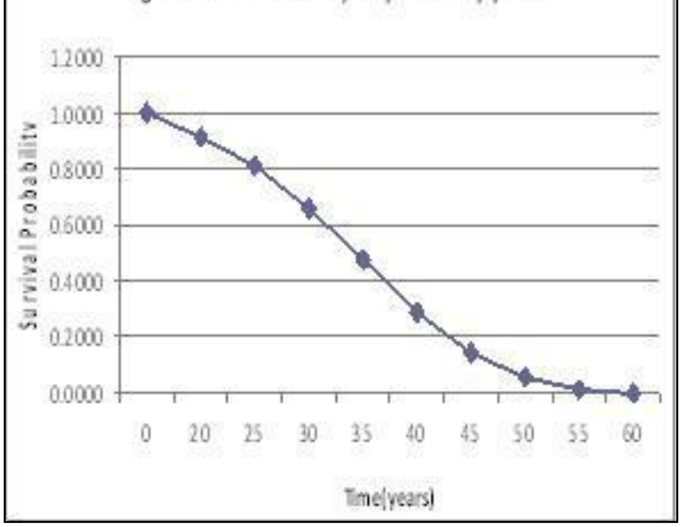


Fig 5f:Survival Probability Graph for S06 pipeline

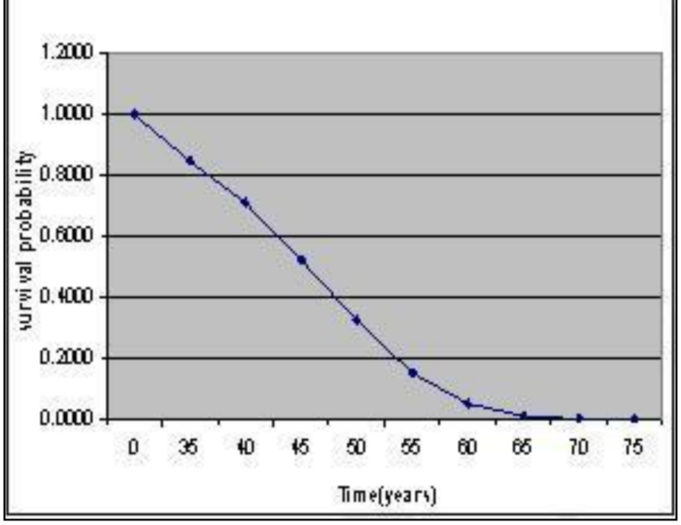


Fig 5g:Survival Probability Graph of S07 pipeline

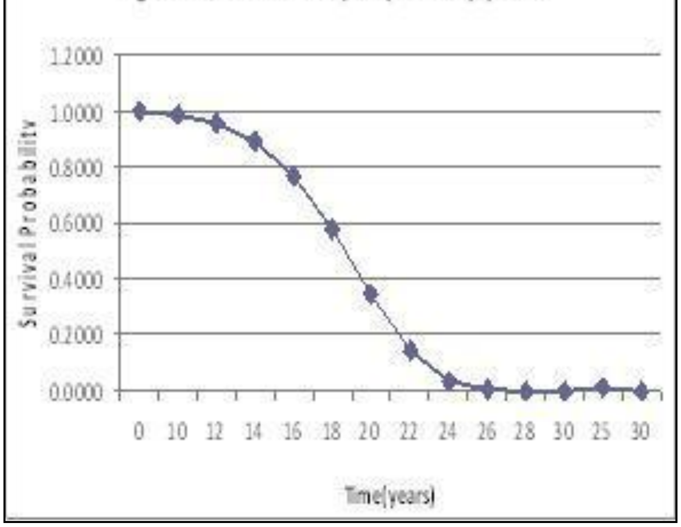


Fig 5h:Survival Probability Graph of S08 pipeline

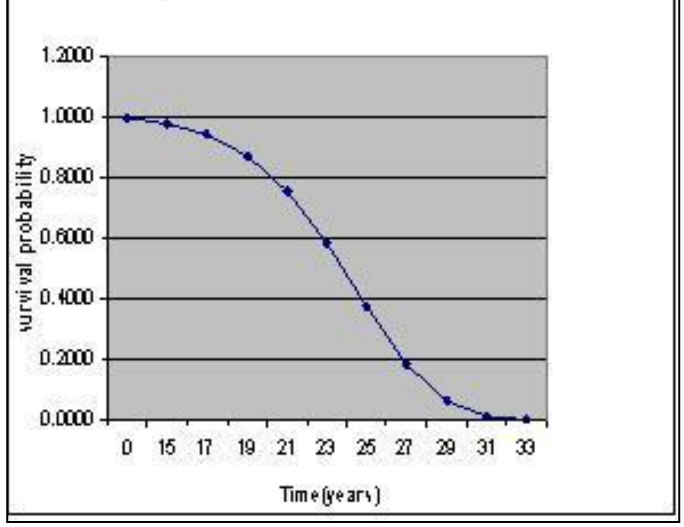


Fig 5i :survival probability of S09 pipeline

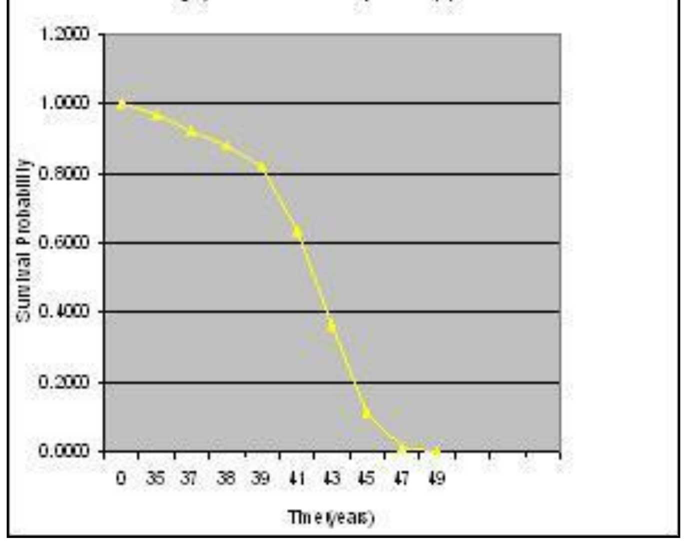


Fig 5j:Survival Probability of S10 pipeline

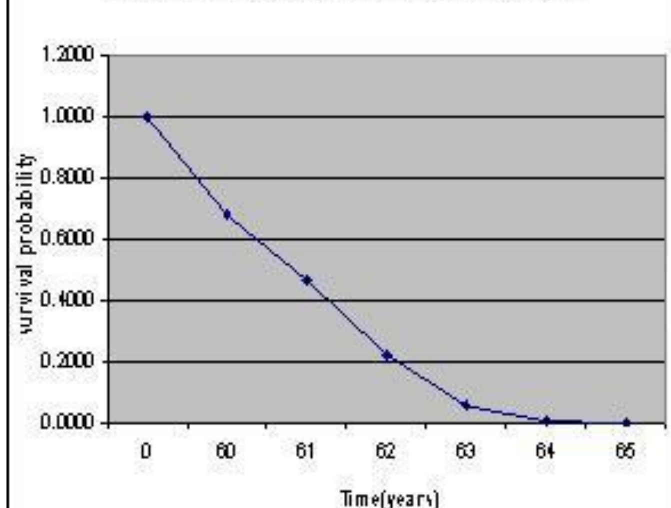


Fig 5k :survival probability graph for S11 pipeline

Table 5: Summary of Monte Carlo simulation Runs

Field		Pipeline Corrosion Rate and Number of random number occurrence via simulation run																	CR_{av}
S01	CR^{freq}	0.02^{1}	0.03^{1}	0.032^{1}	0.04^{4}	0.05^{2}	0.051^{1}	0.06^{1}	0.069^{1}	0.1^{2}	0.12^{1}	0.36^{1}	0.58^{1}						0.105
	FORN	5961	5876	5854	23461	11925	5753	5946	5836	11727	5887	5896	5878						
S02	CR^{freq}	0.020^{1}	0.021^{1}	0.025^{1}	0.03^{1}	0.036^{1}	0.04^{5}	0.047^{1}	0.05^{1}	0.11^{1}	0.12^{1}	0.13^{1}	0.33^{1}	0.77^{1}					0.113
	FORN	5785	5870	5938	5924	5871	29287	5837	5814	5848	5880	5951	6016	5979					
S03	CR^{freq}	0.016^{1}	0.018^{1}	0.02^{1}	0.03^{2}	0.04^{2}	0.05^{2}	0.2^{1}	0.23^{1}	0.26^{1}	0.31^{1}	0.32^{1}	0.33^{1}	0.38^{1}	0.49^{1}				0.165
	FORN	6004	5835	5865	11650	11868	11707	5899	6005	5998	5813	5835	5903	5802	5816				
S04	CR^{freq}	0.02^{1}	0.028^{3}	0.07^{1}	0.08^{1}	0.11^{1}	0.14^{1}	0.17^{1}	0.22^{1}	0.32^{1}	0.39^{1}	0.45^{1}	0.47^{1}	0.5^{1}	0.52^{1}	0.69^{1}			0.25
	FORN	5832	17578	5768	5840	5831	5963	5807	5883	5898	5955	5923	6051	5832	5954	5885			
S05	CR^{freq}	0.007^{1}	0.01^{1}	0.011^{1}	0.02^{2}	0.021^{1}	0.07^{1}	0.088^{1}	0.095^{1}	0.1^{1}	0.107^{1}	0.147^{1}	0.152^{2}	0.192^{1}	0.388^{1}	0.4^{1}			0.116
	FORN	5853	5819	5940	11820	5830	5918	5928	5916	5983	5957	5883	11641	5889	5700	5926			
S06	CR^{freq}	0.012^{1}	0.024^{1}	0.03^{2}	0.037^{1}	0.04^{1}	0.05^{1}	0.053^{1}	0.06^{2}	0.09^{1}	0.096^{1}	0.13^{1}	0.142^{1}	0.148^{1}	0.26^{1}	0.28^{1}			0.091
	FORN	5888	5963	11773	5962	5850	5788	5834	11655	5936	5910	5917	5847	5933	5872	5872			
S07	CR^{freq}	0.001^{1}	0.004^{1}	0.005^{1}	0.012^{1}	0.02^{1}	0.023^{1}	0.03^{1}	0.05^{1}	0.066^{1}	0.07^{1}	0.073^{1}	0.08^{1}	0.085^{1}	0.09^{1}	0.125^{1}	0.126^{1}	0.176^{1}	0.061
	FORN	5915	5824	5883	5759	5987	5991	5952	5865	5858	5904	5806	5771	5846	6008	5963	5778	5890	
S08	CR^{freq}	0.004^{1}	0.01^{2}	0.047^{1}	0.08^{2}	0.099^{1}	0.1^{1}	0.107^{1}	0.109^{1}	0.17^{1}	0.25^{1}	0.27^{1}	0.3^{1}	0.43^{1}	0.46^{1}	0.67^{1}			0.189
	FORN	5890	11779	5949	11774	5743	5846	5852	5779	5835	5907	5924	5947	5904	5927	5944			
S09	CR^{freq}	0.01^{1}	0.02^{1}	0.03^{1}	0.035^{1}	0.04^{1}	0.05^{1}	0.078^{1}	0.08^{1}	0.081^{1}	0.085^{1}	0.09^{1}	0.092^{1}	0.26^{1}	0.27^{1}	0.29^{1}	0.44^{1}	0.47^{1}	0.143
	FORN	5881	5787	5940	5832	5935	5910	5882	5828	5829	5849	5896	5922	5898	5942	5869	5831	5969	
S10	CR^{freq}	0.007^{1}	0.009^{1}	0.01^{2}	0.028^{1}	0.05^{2}	0.06^{1}	0.08^{1}	0.081^{1}	0.09^{2}	0.1^{1}	0.11^{1}	0.13^{1}	0.15^{1}	0.17	0.40^{1}			0.09
	FORN	5888	5963	11773	5962	11638	5834	5858	5797	5936	5910	5917	5847	5933	5872	5872			
S11	CR^{freq}	0.01^{2}	0.011^{1}	0.013^{1}	0.014^{1}	0.015^{1}	0.033^{1}	0.04^{1}	0.051^{1}	0.07^{1}	0.085^{1}	0.086^{1}	0.09^{1}	0.099^{1}	0.12^{1}	0.14^{1}	0.19^{1}		0.063
	FORN	11851	5956	5817	5962	5850	5788	5834	5858	5797	5936	5910	5917	5847	5933	5872	5872		

FORN= Frequency of Occurrence of simulated Random Number, No 0f Trails: 10^{5}

CR_{av} = Average Corrosion Rate (mm/yr); CR^{freq}= Measured Corrosion rate (mm/yr) and Frequency of occurrence