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Reliability Assessment of Offshore Pipeline Due to Pitting Corrosion

Seyed Mohammad Hossein Sharifi[1*], Nima Pirali[2]

[1] *Assistant Professor, Faculty of Mechanical Engineering, Petroleum University of Technology, Abadan, Iran; Sharifi@put.ac.ir*
[2] *MSc. Student in Offshore Structural Engineering, Petroleum University of Technology, Abadan, Iran; n.pirali@mnc.put.ac.ir*

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ABSTRACT

Pitting is one of the most localized forms of corrosion attacks which cannot be detected easily. Pitting decreases the pipe wall thickness and also the pipeline strength against environmental and operational loads. The purpose of this article is to investigate the most common reliability methods for estimating the maximum pitting depth and the effect of internal pressure on the remaining strength of corroded pipelines at different times in its lifetime service based on different failure pressure models using first-order approximation and sampling reliability methods. To investigate the effect of pitting growth and variation of internal pressure on pipeline characteristics, sensitivity analysis with gamma index several times in pipeline lifetime was performed. It is concluded that the first-order reliability method was applicable for ASME failure pressure models, also concluding that internal pressure and pipeline wall thickness are the most effective load and capacity parameters in failure probability of corroded pipelines. The reliability analysis was performed for two pipeline classes and two different pipeline wall thicknesses and it is concluded that the increase in pipeline wall thickness has more effect on decreasing the probability of failure (POF) of the pipeline than using a pipeline with higher classification.

1. Introduction

The aim of the reliability assessment method is to ensure that the structure will remain safe against the environmental and operational loads; considering the damage effects [1, 2]. This assessment has several stages; knowledge about damage mechanism, knowledge about the loading history, inspection and recording data about existing damage, stress analysis using finite element (FE) methods and finally determining structure health using reliability methods [2].

The subsea pipeline plays an important role in offshore industry. The aim of installing them is to transfer the crude oil or gas from well to platform or transfer oil from platform to the terminals [3]. Nowadays, the pipelines are placed at the bottom of the sea and cover the range of miles [4], also, decreasing the pipeline strength due to corrosion, highlights the necessity of reliability assessments [5].

Corrosion can be defined as a deterioration of a metal, due to chemical or electrochemical interactions between the metal and its environment [6]. Corrosion is one of the most destructive factors which affects the health and integrity of subsea pipelines and it is one of the most significant threats to pipelines that may lead to a Loss of Containment [7],[8]. Different types of corrosion attacks can occur in offshore structure and in offshore steel pipeline two types of corrosion can happen, inside and outside corrosion which can be uniform or un-uniform thinning [9]. Thinning the wall due to corrosion can lead to a decrease in resistance against bursting, which is one of the most important design parameters. High uncertainties in corrosion and design parameters, highlight the importance of reliability assessments [9],[10].

Pitting is one of the localized corrosion attacks that can create holes in metal [11]. Pitting corrosion leads to localized destruction of passivity due to contact with moisture that contains halide ions, particularly chlorides [12]. Pitting is defined as a hole with larger depth than its relevant surface diameter. Predicting and finding the small size of pits can only be done by difficult laboratorial test [5]. The time of pit initiation depends on many factors such as material and electrochemical performance of the pipeline [13].

Some studies have been done like M.Orazem's [14] which presents a nonlinear limit state model for the analysis of pipelines in longitudinal directions. A plastic failure will occur due to inability of pipeline wall thickness to withstand against functional loads. Rajang et al [15] proposed a method to estimate the POF of a grey cast iron pipeline by considering that corrosion pits reduce the strength of the pipe. The residual strength of the pipe is calculated by a repetitive model based on corrosion pit measurement and expected corrosion rate. Li et al. [16] expanded a probabilistic model for calculating pipeline corrosion rate. The Monte Carlo simulation was employed to calculate the POF as a cumulative probability distribution function. M.Mahmoodian et al. [17] proposed a methodology for quantitative assessment of the POF of pipeline over a period of time and predicts its service time. To determine the POF of pipeline using time-dependent reliability theory an empirical model for predicting the maximum pitting depth was specified and a limit state was established by the concept of stress intensity in fracture mechanism.

At first, this paper investigates the most common empirical models for estimating maximum pitting depth (MPD) and compares them. Calculating the POF by using failure pressure models (FPM)s and applying first-order reliability method(FORM) and Monte Carlo sampling methods, corresponding with different pipeline classification and pipeline wall thickness, and sensitivity analysis have been done to obtain the effect of pitting growth and internal pressure on POF. The FPMs used in this paper are ASME, DNV and RESTRENG.

2. Methodology

Pitting corrosion is a damaging form of localized metallic corrosion that has been studied for decades. Although the formation of pits consumes only a relatively small amount (mass) of material, the role of pits in serving as defect sites for crack initiation and continuing corrosion can be significant. In addition, halide ions such as chloride (Cl^-) are well known to accelerate corrosion of steel alloys. The mechanism that leads to pitting initiation in the presence of Cl^- which involves the breakdown of a surficial oxidation/passivation film can be explained as penetration of Cl^- species through the film, and ion-adsorption and local thinning, which ultimately leads to film breakdown [5], [12], [13]. There are many models for predicting the maximum pitting depth including short-term and long-term models. Short term models, unlike long-term models, neglect the effect of long-term corrosion which are associated with the anaerobic condition [18]. When there are no data and measurements available and the analyzer has no information about operating condition, the short term models are useful. In this paper the empirical models for prediction of maximum pitting depth are define in Eq 1-3 [19]-[22]:

a) linear model

$$d = \eta T \tag{1}$$

Where in Eq.(1) d stands for maximum pitting depth, η stands for corrosion rate and T stands for exposure time

b) two phase model

$$d = aT + b(1 - e - cT) \tag{2}$$

where in Eq.(2) a stands for final pitting depth it is constant, about $0.3^{mm/y}$, b stands for pitting depth scaling its constant about 6.27^{mm}, c stands for corrosion rate inhibition factor it is about $0.14^{1/y}$

c) power model

$$d = kTn \tag{3}$$

Where in Eq. (3) *k* and *n* are constant values which are considered 2 and 0.3, respectively.

Corrosion rate will remain constant for all time in linear model and it neglects the effects of oxide layer [18], power and two-phase but considering the effect of oxide layer which may affect the corrosion attack rate [22]. Two phase and power models are not similar but the main difference between them is their assumption and first and final measured values for corrosion [19], [22].

In this paper, maximum pitting depth is determined for several times in pipeline lifetime; first year in which the pipeline is almost intact, ten years which DNV believes that the first maintenance was carried out in ten years of pipeline lifetime [23],[24], in 25 years which is the pipeline lifetime, also for the accuracy of result the pitting depth is determined for 5,12,15,18,22,23,24,28,30 years of pipeline lifetime.

2.1. Reliability analysis

Reliability of a member can be defined as the probability of member surviving under various environmental conditions.[7],[8]. Reliability methods are mathematical tools that are used to determine the POF in special conditions with considering uncertainty in both load and capacity parameters. Uncertainties are divided in two classes, including deterministic and accidental [25],[26]. The deterministic uncertainty including measurement error, limited sample numbers or calibration of equipment, accidental uncertainty relates to the nature of material [27]. All uncertainty parameters should be assessed in a special function called limit state function (LSF), the LSF determine as Eq. (4):

$$g(X) = R(X) - L(X) \tag{4}$$

Where in Eq.(4) g(X) stands for LSF, R(X) stands for capacity and L(X) stands for the load.

If capacity and load are calculated separately then LSF is:

$$\mathrm{Pf} = \mathrm{p}(\mathrm{g} < 0) = \int f_R(x) f_L(x) dx \tag{5}$$

Where in Eq.(5) $F_R(X)$ and $F_L(x)$ stand for probability density function for capacity and load, respectively.

Probability of failure and reliability index (RI) can be calculated by mathematical models like FORM, second-order reliability method and Monte-Carlo method [12].
To transfer the input data (X) to normalized space (U), the NATAF transformation can be used [28]:

$$G(U) = g(T-1(u)) \tag{6}$$

Where in Eq. (6) G (U) stands for standard normalized form of LSF.
FORM deals with the approximation of equation (4) which is determined by linearization of LSF in standard normal space at optimal point (U*), which is determined by solving following optimizing problem [25], [29], [30]:

$$U^* = argmin\{\|u\| g(u) = 0\} \tag{7}$$

Where in Eq. (7) U^* stands for optimal point
The normalized standard form for the first term of Taylor series is written as Eq. (8) [31]:

$$(8) G(u) = G1(u) = \nabla G(u^*)(u-u^*) = \|\nabla G(u^*)\|(ß - \alpha u)$$

where in Eq.(8) ∇G stands for gradient vector, α stands for normalized negative gradient row vector and ß stands for RI which is equal to αu^*.
Normalized negative gradient (α) describe in Eq.(9):

$$\alpha = -\nabla G(u^*)/\| - \nabla G(u^*)\| \tag{9}$$

2.2. Limit State Function

To perform a reliability assessment for a corroded pipeline, it's necessary to consider a limit state function for failure pressure of the corroded pipeline under operating condition. Mahmoodian recommends the following limit state for failure pressure of corroded pipeline [32]:

$$G[Q(t), P0] = Q(t) - P0 \tag{10}$$

Where in Eq.(10) Q(t) stands for residual strength and P_0 stands for operating pressure.
To determine the POF of corroded pipeline by reliability methods several FPMS's are recommended by ASME, DNV, Restreng, Zairian, PRCI [5],[6],[33]. The FPMS used for this article are described in Eq 11-16:

a) ASME

$$P_f = 2.2\frac{SMYS}{D}\left\{1-\frac{d}{t}\right\}^t \tag{11}$$

Where in Eq.(11) P_f stands for probability of failure, SMYS stands for yield stress of pipeline, D stands for pipeline diameter. d stands for MPD, t stands for PWT, L stands for projected length of corrosion defects.

$$M = \sqrt{1+0.8(\frac{L}{D})^2\frac{D}{t}} \tag{12}$$

Where in Eq.(12) M stands for bulging factor.

b) PRCI

$$P_f = \frac{2t}{D}SMTS\{1-\frac{d}{t}M\} \tag{13}$$

Where in Eq.(13) SMTS stands for ultimate pipeline strength.

$$M = \{1-\exp\{\frac{-.157L}{\sqrt{\frac{D(t-d)}{2}}}\} \tag{14}$$

c) Restreng

$$P_f = \frac{2*SMTS*t}{d}(1-\frac{\frac{d}{t}}{M}) \tag{15}$$

$$M = \sqrt{1-0.003375(\frac{L^4}{D^2t^2})+0.6275(\frac{L^2}{Dt})} \tag{16}$$

2.3. Sensitivity Analysis

One of the main results of the form is sensitivity analysis that provides information about stochastic variables [11]. It is concluded from Eq.(8) that the mean value of u is zero and is defined as covariant of identity matrix. The variance of G and mean value are calculated as Eq.(17) and Eq.(18) [30]:

$$\mu G1 = \|\nabla G\|^*\beta \tag{17}$$

$$\sigma G_1^2 = \|\nabla G\|^2(\alpha_1^2+\alpha_2^2+\cdots.+\alpha_n^2) \tag{18}$$

It is concluded from Eq. (17) that β is Reliability index for linearized problem. Eq. (18) shows that positive and negative values of α_i are indication that random variable u_i is of load and capacity, respectively [29].

$$G_1(u) = \|\nabla G\|(\beta - \alpha_1 u_1 - \cdots - \alpha_n u_n) \tag{19}$$

Alpha index can be used for independent parameters, for correlated parameters other index like gamma should be used. The gamma index is obtained by following equation [34],[35]:

$$\gamma = \alpha J_{u,x}D\| \alpha J_{u,x}D\| \tag{20}$$

Where in Eq.(20) γ stands for gamma index, D stands for standard deviation of u(x), $J_{u,x}$ stands for joint normal distribution. In this research data is correlated so gamma index is used for performing sensitivity analysis.

2.4. Target Safety Level

It is necessary to define a safety level before performing the reliability assessment, based on considered safety level and operation type, the maximum POF can be calculated based on codes.
DNV-OS-F101 recommends target safety level for different scenario which is showed in Table 1. As bursting is part of Ultimate Limit State (ULS) categories and pipeline safety level is considered as high class, the target POF for pipeline with high class safety level is considered 10^{-6}.

Table 1. Target POFs [23]

Limit state categories	Safety Level			
	Low	**Medium**	**High**	**Very High**
Ultimate limit state	10^{-4}	10^{-5}	10^{-6}	10^{-7}
Service limit state	10^{-2}	10^{-3}	10^{-3}	10^{-4}
Accidental limit state	10^{-5}	10^{-6}	10^{-7}	10^{-8}
Fatigue limit state	10^{-3}	10^{-4}	10^{-5}	10^{-6}

3. Case study

The pipelines characteristic used in this paper presented in table 2 and 3:

Table 2. Pipeline API-5L-X65 specification

Row	Parameters	Value	unit
1	Wall thickness	0.0243	m
2	Diameter	0.9144	m
3	SMTS	540	MPa
4	SMYS	450	MPa
5	Young module	210	GPa
6	Water depth	85	m
7	Water density	1025	kg/m^3
8	Submerged weight	4273	N/m

Table 3. Pipeline API-5L-X70 specification

Row	Parameters	Unit	Value
1	Thickness	0.0243	m
2	Diameter	0.9144	m
3	SMTS	570	MPa
4	SMYS	490	MPa
5	Young module	210	GPa
6	Water depth	85	m
7	Water density	1025	kg/m^3
8	Submerged weight	4273	N/m

In order to carry out a comprehensive probabilistic assessment on pipeline, all effective parameters are considered as inherent uncertain parameter and their relevant distributions are in accordance with newest recommendations [5], [8], [24].
Uncertainties considered for this assessment are as follow:

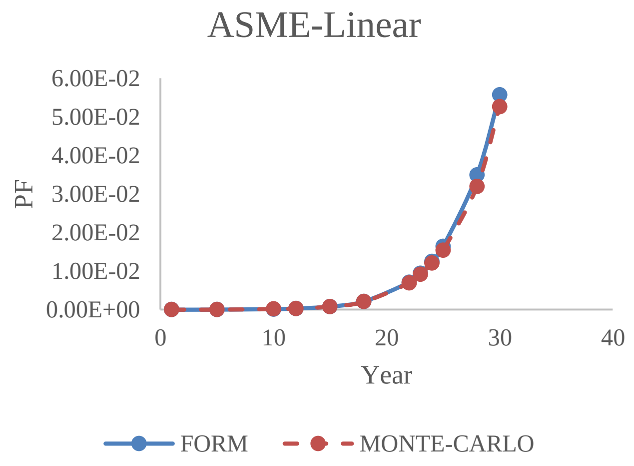
Table 4. Uncertainty of parameters

Row	Parameters	Distribution type	C.O.V
1	Diameter	Normal	0.1
2	PWT(t)	Normal	0.05
3	MPD(d)	Weibull	variable
4	Crack length(L)	Log-normal	variable
5	Crack width(W)	Gamma	0.158
6	Operating pressure(P_o)	Normal	variable
7	SMYS	Normal	0.1
8	SMTS	Normal	0.1

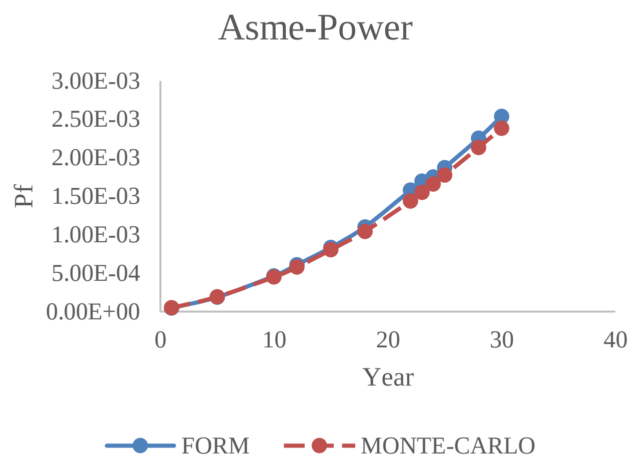
4. Results and Discussion

By using recommended FPMs and considering uncertainty in table 4, POF is calculated using RISK TOOL (RT) software corresponding three corrosion models and three FPMs and also different pipeline classification and pipeline wall thickness. The following figure shows the relationship between the POF and exposure time:

(a)



(b)



(c)

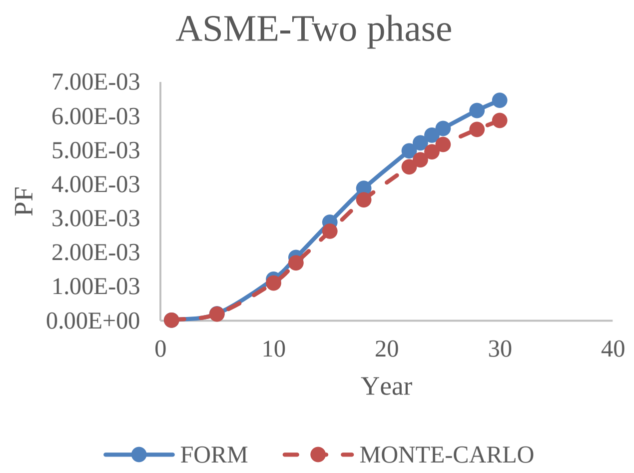
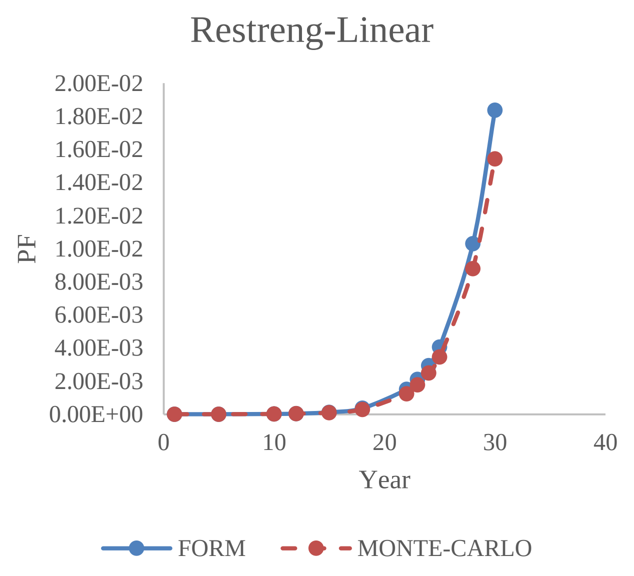
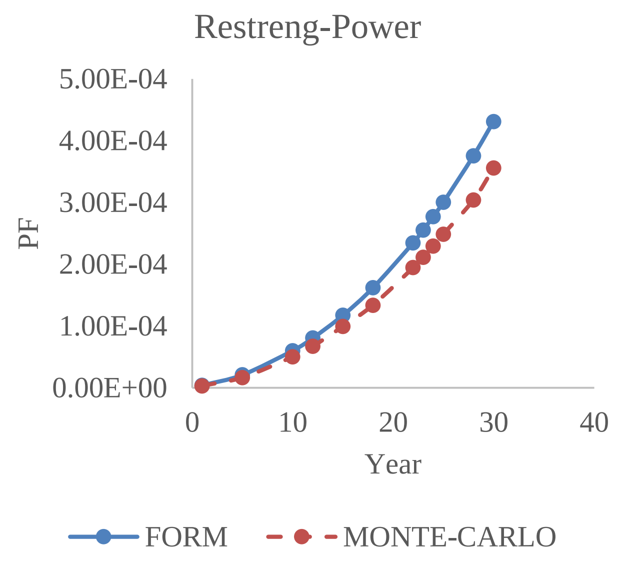


Figure 1. POF of API-5L-X65 for ASME FPM; (a): linear model, (b): power model, (c): Two-phase model

(a)



(b)



(c)

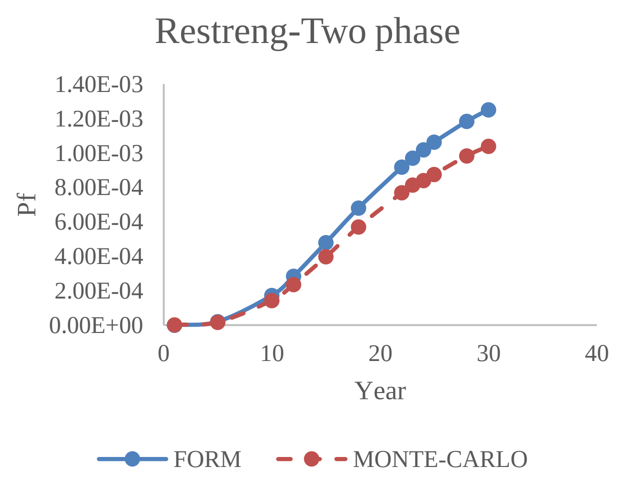
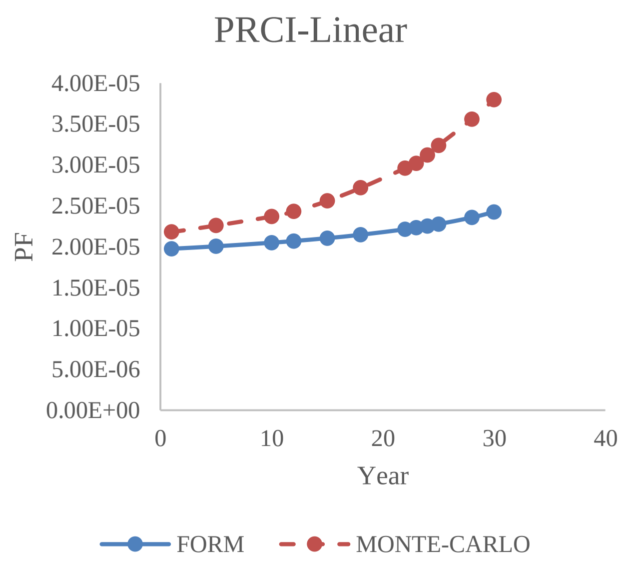
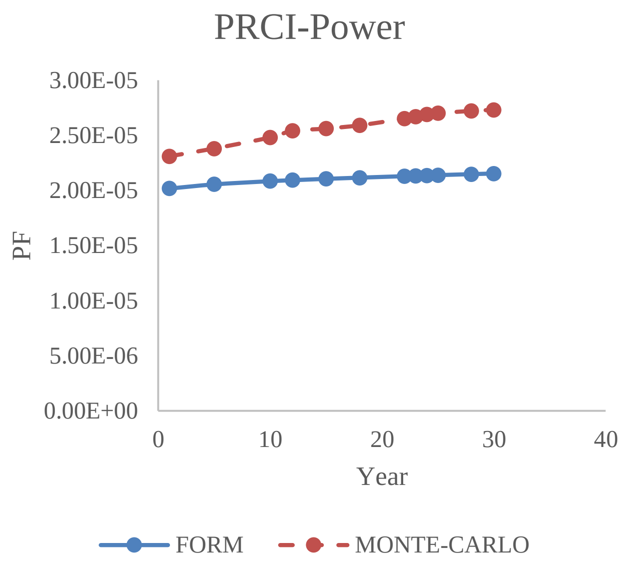


Figure 2. POF of API-5L-X65 for Restreng FPM; (a): linear model, (b): power model, (c): Two-phase model

(a)



(b)



(c)

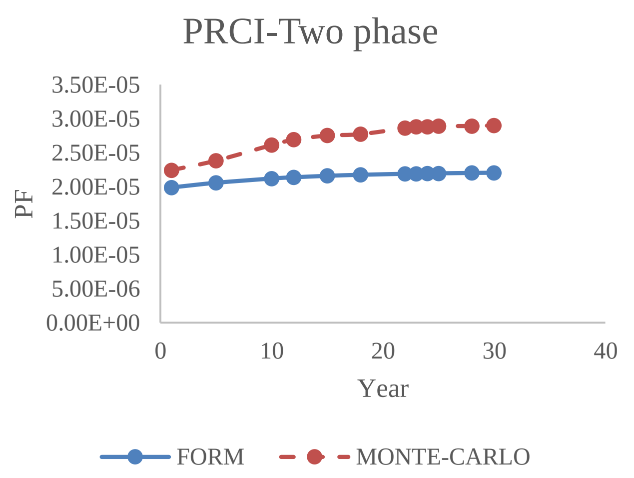
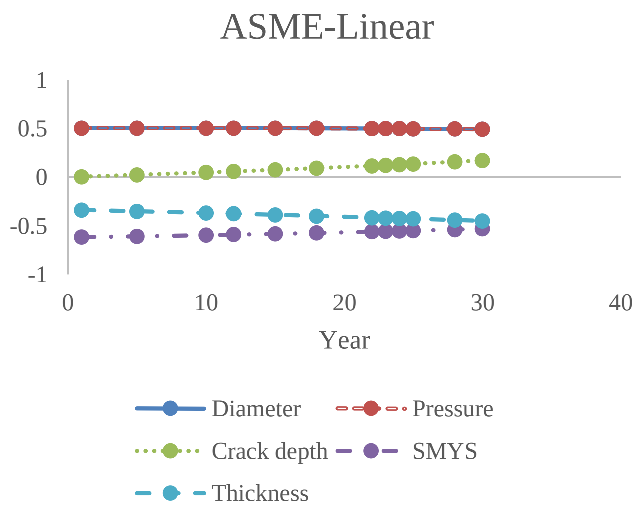


Figure 3. POF of API-5L-X65 for PRCI FPM; (a): linear model, (b): power model, (c): Two-phase model

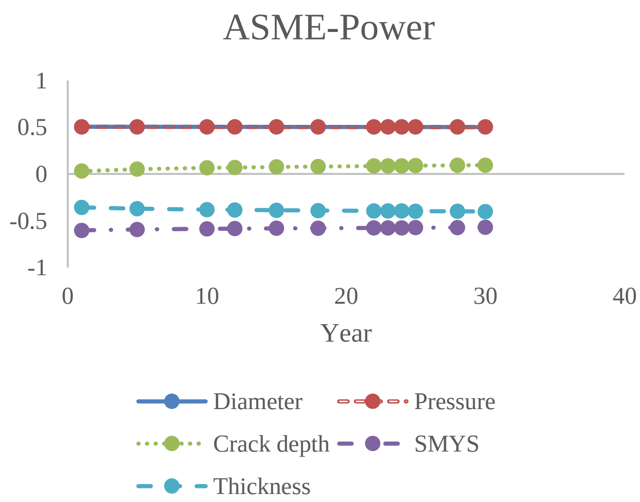
As shown in figure 1 and figure 2 and figure 3, in comparison with target POF (10^{-6}), failure will occur in

all FPMs. PRCI shows the lowest POF and it is more optimistic. Asme and Restreng consider higher POF which increases the need for planning for preventive measure such as inspection based on risk or reliability, or using pipeline with higher wall thickness (after cost evaluating) which increases the safety and decreases the bursting. ASME FPM, because of proximity of results between FORM and Monte-Carlo, has more accuracy than Restreng and PRCI. Periodic inspection (schedule by result of reliability analysis) of pipeline with pig and determining the corroded point and pit depth can lead to a decrease in POF and bursting probability. Using different empirical models for pitting depth affect the pipeline maintenance cost directly, using linear model causing higher POF especially for ASME. Unlike the linear model, two-phase and power models consider film layer [22] but power model can lead to more acceptable result.
To determine the change of importance of each parameter and their effect on pipeline failure, a sensitivity analysis for ASME FPM with gamma index was conducted and result as follow:

(a)



(b)



(c)

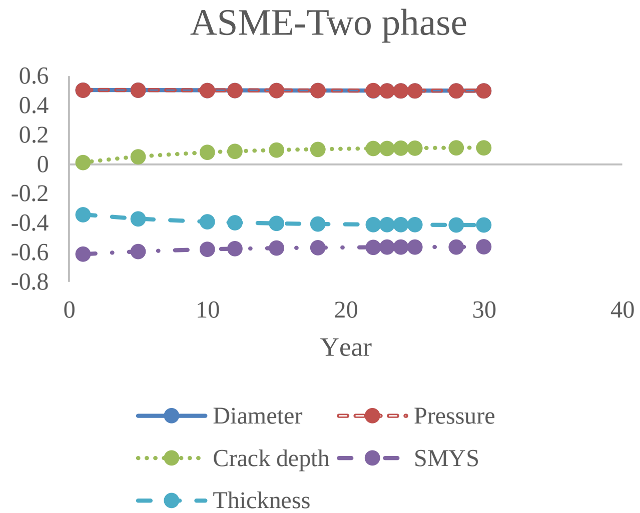
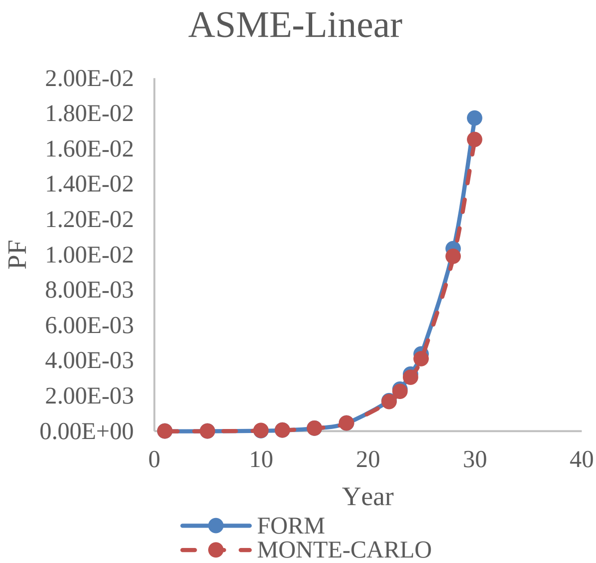


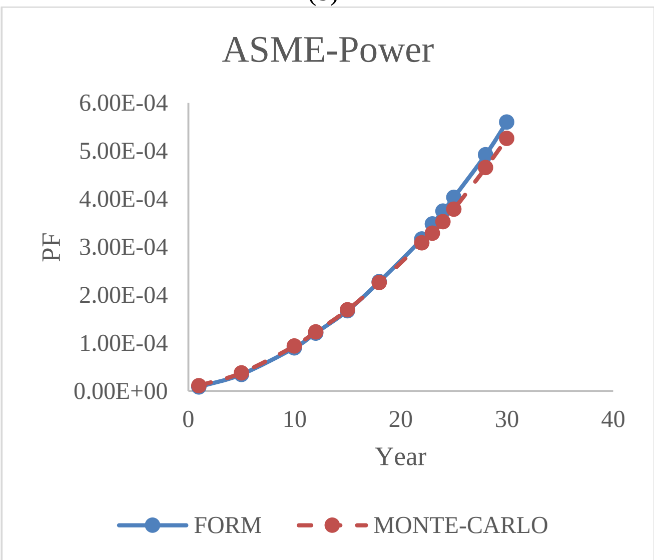
Figure 4. Sensitivity analysis of API-5L-X65 for ASME FPM; (a): linear model, (b): power model, (c): Two-phase model

As shown in figure 4, the most effective parameters for probability of failure of pipeline are pressure as load parameter and SMYS as capacity parameter. Also with increasing the pitting depth in time, diameter and pressure don't change (they are independent from corrosion) but the SMYS as a capacity parameter decreases in time. Sensitivity analysis gives the employer an option to make a decision based on parameters which affect the safety of pipeline and with a cost effective work prevents the pipelines from bursting.
In accordance with results of sensitivity analysis the two parameters which have more effect on pipeline safety are wall thickness and SMYS. In the following the effect of increasing the wall thickness (using API-5L-X65 with 25.4mm wall thickness) and SMYS (by using high class pipeline API-5L-X70) on POF has been investigated and results are shown in figure 5 and figure 6, respectively:

(a)



(b)



(c)

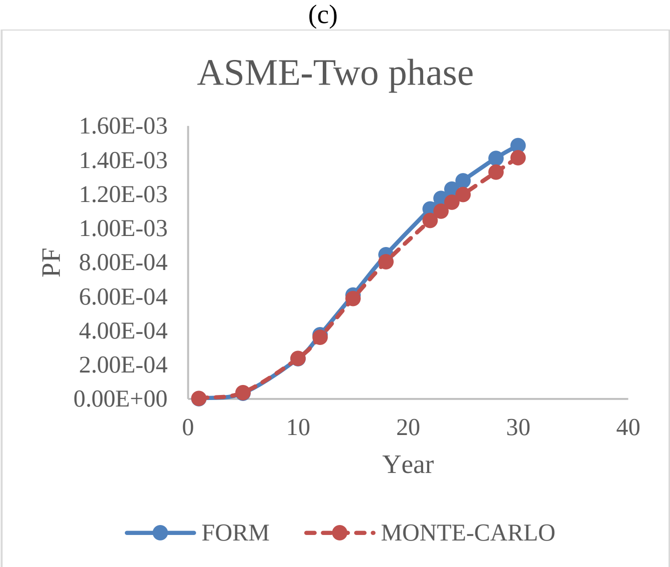
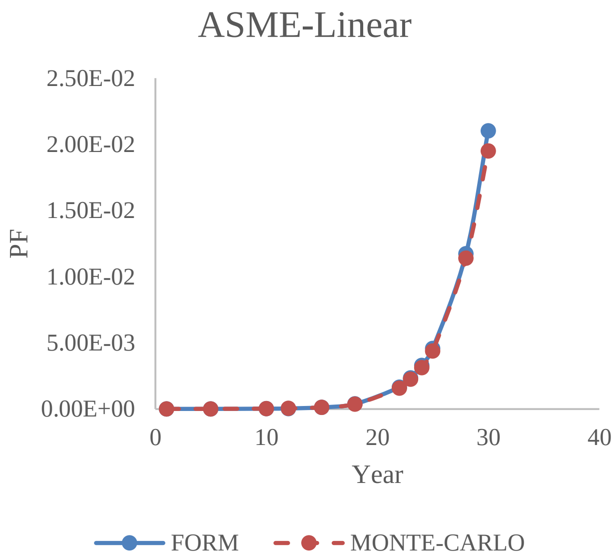
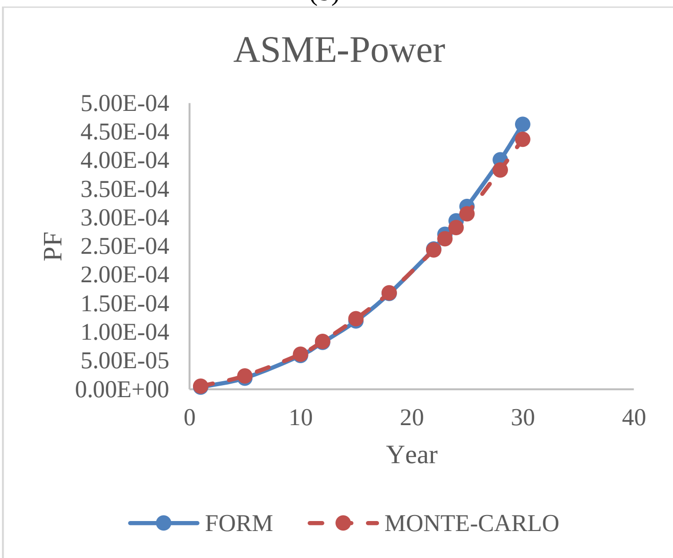


Figure 5. POF of API-5L-X65 t=25.4mm for ASME FPM; (a): linear model, (b): power model, (c): Two-phase model

(a)



(b)



(c)

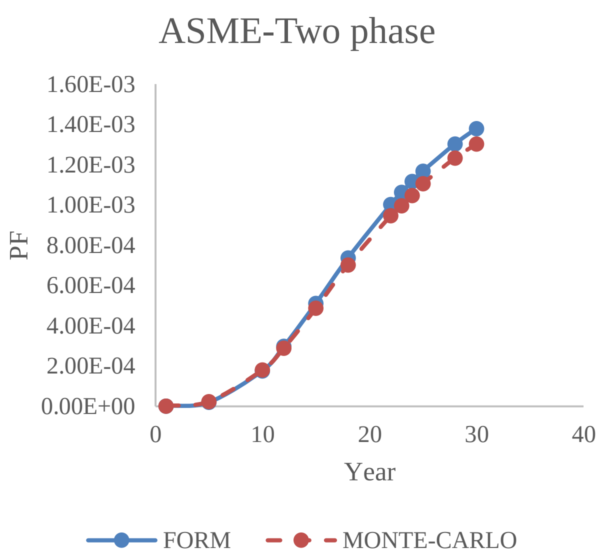


Figure 6. POF of API-5L-X70 for ASME FPM; (a): linear model, (b): power model, (c): Two-phase model

As shown in figure 5 and figure 6, the POF for both API-5L-X65 with 25.4mm wall thickness and API-5L-X70 has decreased, but increasing the wall thickness for 4.72% leads to more decrease in POF. The POF decreased about 213.8% when the thickness will increase about 4.72% but the POF decreased 164.9% using pipeline with higher classification. After cost evaluating, the employer can choose the best condition.

5. Conclusion

In this paper, the most common models for estimating the pitting depth were investigated. With using probability of failure theory the safety of a pipeline against bursting due to pitting corrosion was investigated, considering three FPMs and different pipeline classifications and wall thicknesses and it is concluded that:

- The first reliability method for investigating the POF of pipeline, considering the ASME FPM leads to more accurate results and also using power models for predicting the pitting depth has more accurate results than other empirical models.
- Pitting corrosion in pipeline leads to the increasing of the POF against bursting, so periodic inspection scheduled by reliability analysis is necessary to predict the corroded point and corrosion rate to reduce the POF against bursting.
- Sensitivity analysis shows that the two parameters which have more effect on pipeline safety are wall thickness and SMYS, by increasing the pipeline wall thickness about 4.7% the POF against bursting will decrease about 213.8% and using higher class pipeline decreases the POF about 164.9%, it provides the employer with better prospective to choose the best option for pipeline to decrease the POF with more cost efficiency.

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