Comparative Studies on Assessment of Corrosion Rates in Pipelines as Semi-Probabilistic and Fully Stochastic Values

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ABSTRACT: Reduction of pipeline carrying capacity and safety are often caused by corrosion and its potential damaging effects. Simple techniques which can be used to evaluate both current and the time-dependent change in the pipeline's reliability are needed since reliability analysis is recognized as a powerful decision-making tool for risk-based design and maintenance. The prediction of future sizes of growing defects and the pipeline remaining life time are obtained by using consistent assessments of their Corrosion Rates (CRs); and these CRs may be considered as deterministic, semi-probabilistic or fully stochastic values. The idea of predicting future sizes of growing defects and corrosion rates as semi-probabilistic and fully stochastic values is considered with a comparison of the results conducted and implemented on a real life pipeline. In this contribution, a probabilistic method based on the imprecise probability approach is presented to predict the remaining life time and the failure probability of pipelines with corrosion defects by using the Monte Carlo simulation (MCS) method implemented in OpenCossan; the open source engine of COSSAN software for uncertainty quantification and risk management. The results obtained from deterministic, semi-probabilistic and probabilistic methods are compared using B31G, Modified B31G and DNV-101 pressure failure models. The proposed probabilistic method of assessment can be applied for the design of new systems as well as assessing of existing pipelines in operation.

One of the most important degradation/ deterioration mechanisms that affect the long-term reliability and integrity of metallic pipelines is corrosion; even though the damage done by the surrounding environment (aggressive environments) results in degradation of pipelines, particularly steel, the most dominant form of degradation remains corrosion. See e.g. Ahammed, (1998) and Caleyo, et. al. (2002). Corrosion which leads to metal loss both in type and section (length and depth) is the most prevailing time dependent threat to the integrity, safe operation and cause of failure for oil and gas pipelines (Bazan and Beck, 2013).

Uncertainties such as in relation to operational data variation, randomness of environment and imperfect measurement of the tool; associated with pipeline geometry, material strength, operating pressure and inspection tool, in addition to aging of the pipeline make it a complex scenario in reduction of the accuracy of pipeline future assessment/remaining life estimation; Ahammed, (1998), Caleyo, et. al. (2002) and Qian, et. al. (2011).

The remaining strength of pipeline with corrosion defects can be assessed using one or all of the international design codes viz: B31G, B31Gmod, Battelle, DNV-101 and Shell-92. These methods of assessing corroded pipeline's remaining strength use deterministic values for load and resistance variables, thereby assuming no uncertainty, but there are inherent uncertainties in corrosion process- such as defect dimensions and material properties- and operational condition- like operating pressure and human factors. However, this approach cannot provide enough quantitative information for estimation of probability of failure of a corroded pipeline with time due to changes in the load and resistance variables during its service life. Hence, the need for probabilistic methods of remaining life estimation which is more robust than deterministic analyses, which can be used to evaluate the pipeline's current reliability and the time-dependent change in reliability. From the initial developments, imprecise probabilities have emerged into several application fields in engineering with structured approaches. The largest application field appears as reliability assessment, where imprecise probabilities are implemented to address sensitivities of the failure probability with respect to the probabilistic model choice (Beer et. al (2013). This contribution therefore proposes robust method for predicting remaining strength for corroded pipeline, which works with reliability metric redefined within the framework of imprecise probabilities.

1. CORROSION RATE ASSESSMENTS

For any type of analysis of the future state of a pipeline, such as failure probability, residual strength, etc., it is based on the predicted sizes of the defects which were detected during In-Line Inspection (ILI). The defect parameters at a given time, t for a linear rate of the length and depth of corrosion can be assessed, as in Timashev and Bushinskaya (2010); CRs are assumed as constant values:

$$d(t) = d_0 + v_d.t \qquad (1)$$

$$l(t) = l_0 + v_l.t \qquad (2)$$

Where v_d and v_l are the CRs in the radial and longitudinal directions, respectively; d_0 and l_0 are ILI data for depth and length of defect respectively.

CRs are defined differently if two results of ILI are available, as:

$$CR = \frac{P_L - P_p}{t_L - t_p} \qquad (3)$$

P_L and P_P are sequential defect parameters during ILI; and the corresponding times of conducting ILI are t_L and t_P respectively. CRs are represented as random variables in real life.

2. PRESSURE FAILURE MODELS

Three failure pressure models were used to compute the pipeline pressure failure, namely; B31G, DNV-101 and Modified B31G. All these models were used as deterministic and probabilistic values, while DNV-101 model was used alone as semi-probabilistic values. See ASME-B31G (1991& 1995) and DNV (1999). More details will be discussed later in section 3.1.1.

B31G Code

$$P_f = 1.11\frac{2\sigma_y t}{D}\left(\frac{1-\frac{2d}{3t}}{1-\frac{2d}{3t}M^{-1}}\right) \text{ for } G<4 \qquad (4)$$

$$P_f = 1.11\frac{2\sigma_y t}{D}\left(1-\frac{d}{t}\right) \text{ for } G\geq 4 \qquad (5)$$

$$G = 0.893\frac{L}{\sqrt{Dt}},\ M = \sqrt{1+0.893\frac{L^2}{Dt}} \qquad (6)$$

Modified B31G Code

$$P_f = \frac{2(\sigma_y + 68.95)t}{D}\left(\frac{1-0.85\frac{d}{t}}{1-0.85\frac{d}{t}M^{-1}}\right) \quad (7)$$

$$M = \sqrt{1+0.6275\frac{L^2}{Dt} - 0.003375\frac{L^4}{D^2t^2}} \quad (8)$$

for $L^2/Dt \leq 50$

$$M = 0.032\frac{L^2}{Dt} + 3.3 \quad \text{for } L^2/Dt > 50 \quad (9)$$

DNV-101 Code

$$P_f = \frac{2\sigma_u t}{D-t}\left(\frac{1-\frac{d}{t}}{1-\frac{d}{t}M^{-1}}\right) \quad (10)$$

$$M = \sqrt{1+0.31\frac{L^2}{Dt}} \quad (11)$$

$$P_f = \frac{\gamma_m 2t\sigma_u \left(1-\gamma_d (d/t)^*\right)}{(D-t)\left(1-\gamma_d (d/t)^* M^{-1}\right)} \geq MAOP \quad (12)$$

$$(d/t)^* = (d/t)_{measured} + \varepsilon_d .StDev(d/t) \quad (13)$$

$$StDev[d/t]_T = \sqrt{(StDev[d/t]_0)^2 + \frac{T^2}{t^2}StDev[cr]^2}$$

(14)

Where P_f = failure pressure, d = defect depth, D = outside diameter of pipe, t = wall thickness of the pipe, L = the longitudinal length of defect, σ_y = Material yield stress, σ_u = ultimate tensile strength, M = Folias factor, γ_d = partial safety for the defect, γ_m = partial safety factor for inspection method, ε_d = fractile factor value, $(d/t)_{measured}$ = measured relative corrosion defect, StDev(d/t) = standard deviation for measurement (d/t) ratio and MAOP = maximum allowable operating pressure. StDev $[d/t]_T$ = standard deviation of inspection tool in future, StDev$[d/t]_0$ = standard deviation of inspection tool in the first year of assessment, Std[cr] = standard deviation of corrosion, and T = prediction interval time.

3. UNCERTAINTIES IN CORROSION ASSESSMENT

Prediction of future sizes of growing defects and corrosion rates in pipeline as a task has always been a difficult and complex one, due to some uncertainties involved in the data on metal loss; the lower bound (mean value) data are usually taken as the input data, which is the average value of each parameter in calculation. Likewise, the operating conditions and processed fluids (such as Oil) over time will definitely affect the deterioration of the system. Hence the need for allowance for gaps in data and uncertainty. One of the important features of imprecise probabilities as reported in Beer, et. al. (2013), is the identification of bounds on probabilities for events of interest; the uncertainty of an event is characterized with two measure values, namely a lower probability and an upper probability.

3.1. Deterministic values

Based on developed capacity equations or codes, deterministic procedures are straight forward. The three pressure failure models outlined above were used to assess the corroded pipeline, the average values of the variables of load and resistance are taken for the calculation; without considering any inherent uncertainties.

3.1.1. Semi-probabilistic values

DNV-101 code is used for the semi-probabilistic assessment. In this code, safety factors have been incorporated to take care of uncertainties particularly for defect depth and pressure failure (burst) capacity. To predict the remaining future pressure, the partial safety factors for inspection method, defect and fractile value were increased, as a function of time to make up for the inherent uncertainties in corrosion rate, materials and environmental properties, as shown in eqns.(12) and (13). Then, the standard deviation of the inspection tool as a function of the pipeline operation time was obtained using eqn. (14). See e.g. DNV (1999); Noor, et. al. (2010).

3.1.2. Stochastic values

In reliability based corrosion management, reliability analysis, is increasingly adopted in pipeline operations, this involves: detection of corrosion defects through ILIs; determination of probability of failure of the pipeline from data of inspection results and repair of defects as may be deemed necessary. From eqns. (1) and (2), the corrosion rates are assumed to be constant, that is the corrosion defect size grows with time. Also, the limit state function is defined as the difference between the failure pressure of the pipeline and the operating pressure, expressed mathematically as:

$$LS = P_f - p \tag{15}$$

The probability of failure for the pipeline is written as:

$$PoF = P(LS \leq 0) \tag{16}$$

Where, LS = the limit state function, P_f = the pressure failure, p = the operating pressure, and PoF = probability of failure.

Since analytical methods are inadequate for solving eqn. (16), Monte Carlo simulation (MCs) is employed to calculate the probability of failure; for more flexibility and room for improvement on the models as against FORM and SORM. Large number of 10^5 simulations of realization of the random variables are generated according to probability functions and statistical distributions (see Table 1), as an input into the limit state function, and then implemented in OpenCossan - the open source engine of COSSAN software for uncertainty quantification and risk management; Patelli, et. al. (2014).

For the effect of imprecision on the failure probability: The corrosion defect depth and length, as the most important variables in the failure pressure models are assigned an interval of 150 – 250 mm (defect length), and 0 to 100% as measured defect depth through the nominal wall thickness; representing epistemic uncertainty in the probabilistic procedures. Simulations were run and the bounds of the defect depth calculated and repeated for different level of uncertainty using B31G, DNV-101 and Modified B31G models.

3.2. Example Application

In order to demonstrate the usefulness and applicability of corrosion rates as semi-probabilistic and fully stochastic values, a real life pipeline with a known corrosion is considered. Pigging data was gathered through in-line inspection activities using Magnetic Flux Leakage (MFL) intelligent pig, whereby the values of parameters in the model is a result of the operations and inspection histories of the pipeline as well as in literature (Bazan and Beck, 2013; Qian, et. al. (2011); Caleyo, et. al. (2002); Ahammed, 1998). The pipeline characteristics are as follows: diameter is 609.6mm, wall thickness is 9.52mm, MAOP is 2.76 MPa, design pressure is 4.96 MPa, SMYS is 358 MPa, UTS is 496 MPa and material grade is X52. The evaluation of remaining strength and reliability assessment of the pipeline with defect is carried out using both DNV-101 code for semi-probabilistic values and B31G and B31Gmod codes for stochastic values. Historical data representing metal loss type and parameters (length and depth) are used for determining the corrosion growth rate.

For simplicity, the measured maximum defect depth is about 30% of the nominal wall thickness or 3mm, measured defect length is 200mm; an assumption that more than one identical defects have been detected and measured during ILI, also linear growth model (although relevant for non-linear growth as well) is assumed for the corrosion defects, thereby making a constant growth rates for the length and depth of the corrosion but with uncertainties.

Partial safety factors are introduced in inspection method, defect depth and fractile value to mitigate uncertainties such as in relation to operational data variation, randomness of environment and imperfect measurement of the tool. Low, normal and high safety classes were considered both for a relative inspection method (MFL) and inspection sizing accuracy with 90% confidence level. The partial safety factor for inspection method, (γ_m) of low, normal and high safety classes are taken to be 0.79, 0.74 and 0.70

respectively; standard deviation of defect depth to wall thickness ratio for MFL tool based on relative sizing accuracy of ±0.10 of wall thickness and 80% confidence level is taken to be 0.03. Also, the partial safety factors for defect depth, (γ_d) and fractile value, (ε_d) of all the safety classes are 1.16 and 0.0 respectively.

Table 1: Stochastic model used for the corroded pipeline

Variable	Symbol	Unit	pdf	Mean	CoV
Diameter	D	mm	N	609.6	0.02
Defect depth	d	mm	N	3	0.1
Wall thickness	wt	mm	N	9.52	0.02
Ultimate Tensile Strength	σ_u	MPa	LN	496	0.07
Pipe Yield Stress	σ_y	MPa	N	358	0.07
Defect length	l	mm	N	200	0.1
Operating Pressure	p	MPa	LN	4.96	0.1

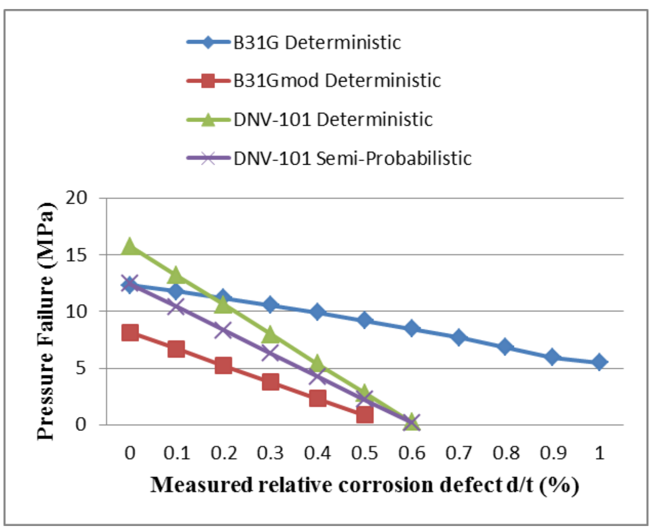

Figure 1: Pressure failure of the corroded pipeline in accordance with B31G, B31G Modified and DNV-101codes as deterministic and semi-probabilistic values.

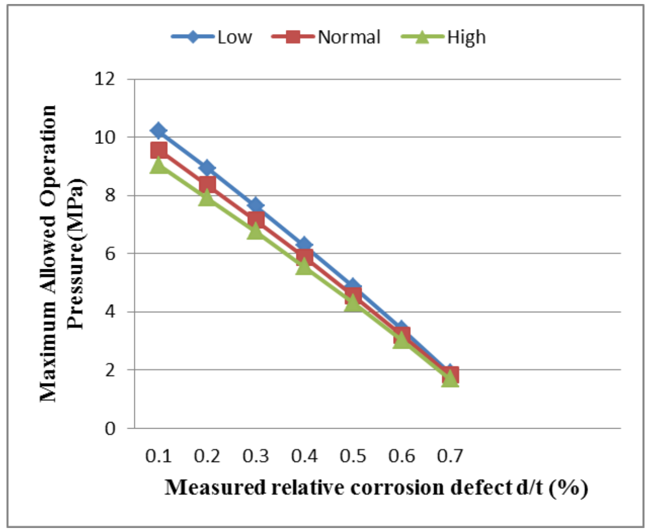

Figure 2: Maximum allowed operation pressure of the pipeline as a function of safety class classification, quality of pipe, inspection method and sizing accuracy of the inspection tool using DNV-101pressure failure model (Semi-probabilistic approach)

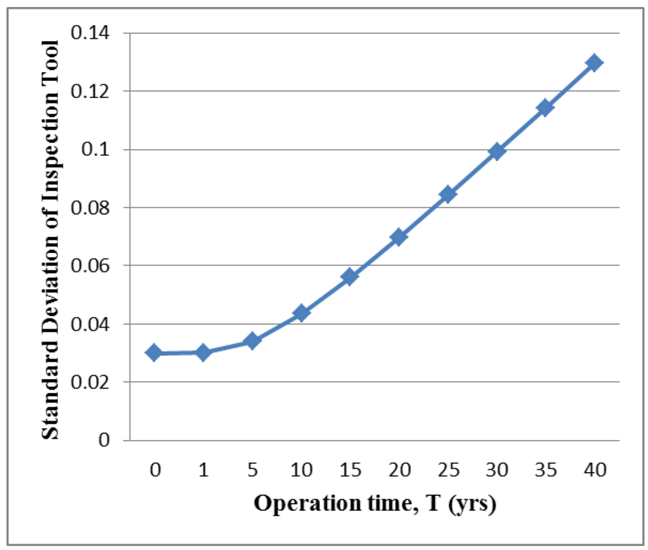

Figure 3: Standard deviation of the inspection tool as a function of the pipeline operation time (DNV-101: Semi-probabilistic approach).

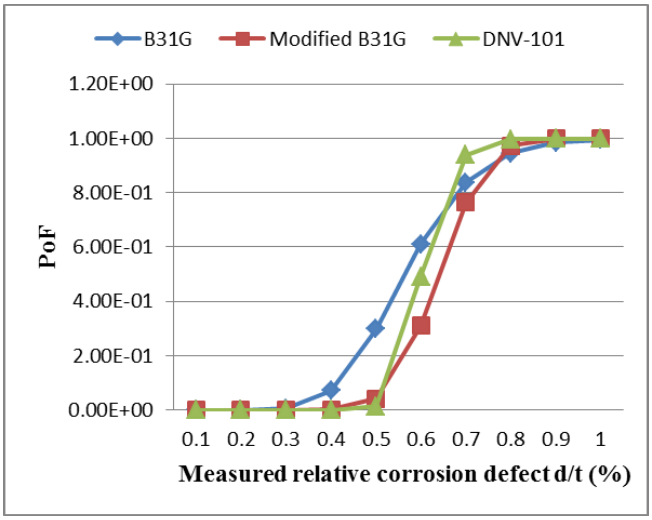

Figure 4: Probability of failure of the pipeline as a function of the pressure failures and measured relative corrosion defect (B31G, Modified B31G & DNV-101codes).

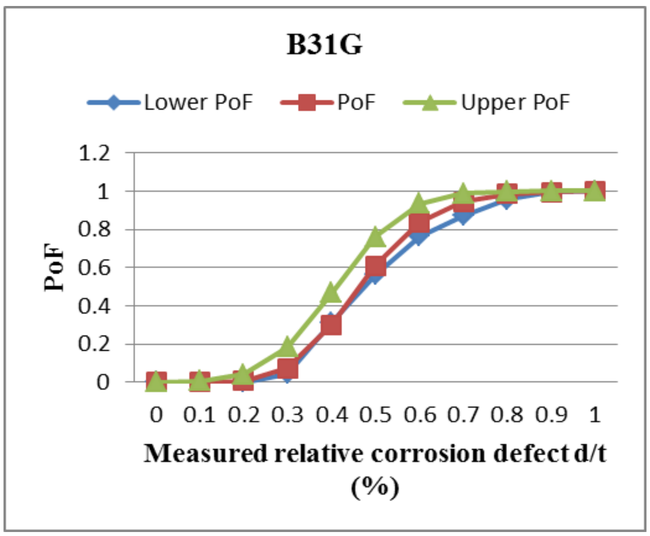

Figure 5: Pipeline probability of failure as a function of assigned epistemic uncertainty on defect length variable using B31G failure pressure model.

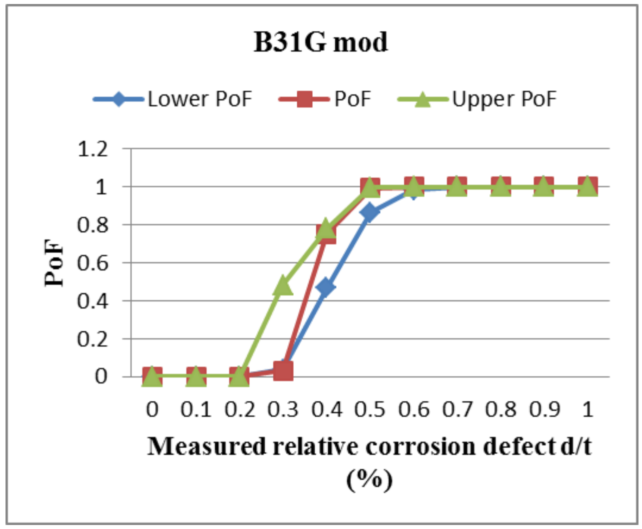

Figure 6: Pipeline probability of failure as a function of assigned epistemic uncertainty on defect length variable using Modified B31G failure pressure model.

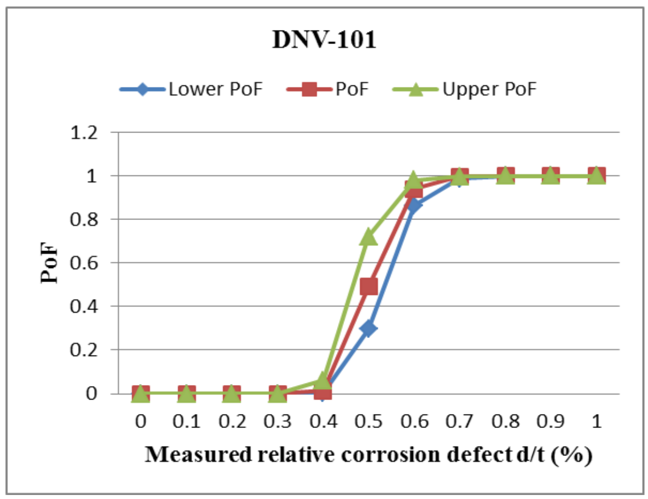

Figure 7: Pipeline probability of failure as a function of assigned epistemic uncertainty on defect length variable using DNV-101 failure pressure model.

3.3 Results and discussion

The pressure failure of the corroded pipeline at different measured relative corrosion defect is calculated by deterministic and semi-probabilistic methods based on the B31G, Modified B31G and DNV-101 models as shown in Fig. 1. It is seen that the B31G model is more conservative, followed by DNV-101 model (both deterministic and semi-probabilistic values), and

Modified B31G model gives the most non conservative result for the corroded pipeline; because of the removal of several conservative simplifications (e.g. Folias' bulging factor, flow stress) in an effort to be a bit more accurate.

The maximum allowed operation pressure for the low, normal and high safety classes in DNV-101 model was explored, alongside with the quality of pipe, inspection method and sizing accuracy of the inspection tool. Fig. 2 shows the result; this also indicates a conservative result. The plot of standard deviation of inspection tool in the future against the operation time is shown in Fig. 3, it indicate increments per time; which implies that the pipeline should be inspected no later than the fifth year for every condition of operating pressure.

Unlike in deterministic and semi-probabilistic procedures, where all variables are taken to be constant and partial safety factors are adopted in the pressure failure models, stochastic method is quite different. All the variables randomly distributed following probabilistic functions and statistical distribution, this in a bid to quantify uncertainties in corrosion growth rates. In Fig. 4, probability of failure as a function of the pressure failures and measured relative corrosion defect is shown. Probability of failure of the corroded pipeline increases with increase in measured relative corrosion defect. It is highly conservative in B31G model followed by DNV-101 model and the least in Modified B31G model.

Figs. 5-7 are the probabilities of failure for the corroded pipeline as a function of assigned intervals on the defect length. All the models (B31G, DNV-101 and Modified B31G) are considered for the effect of uncertainties on the corroded pipeline. Results show that considering epistemic uncertainty, DNV-101 and B31G models provides basically the same results while Modified B31G model still produce significant higher values of probability of failure (PoF) for lower values of measured maximum defect depth through the nominal wall thickness (d/t); when the lower and upper probability bounds were assigned. This could be due to the original but more complex calculation of Folias' bulging factor being restored, the flow stress that was approximated as SMYS plus 68.95MPa, and the net area of metal loss in a longitudinal cross section through the corroded area approximated as 85% of a uniform-depth defect having the same maximum length and depth as the actual defect.

4 CONCLUSIONS

This work presents the prediction of future sizes of growing defects and corrosion rates as semi-probabilistic and fully stochastic values with a comparison of the results conducted and implemented on a real life pipeline. The effect of the measured relative corrosion defect on the pressure failure, maximum allowed operation pressure and the pipeline probability of failure were studied.

The following conclusions are drawn:

- The pipeline probability of failure increases with the increased measured relative corrosion defect, as well as the operation time.
- The pressure failure is higher both in B31G and DNV-101 models than in Modified B31G using deterministic and semi-probabilistic procedures.
- The deterministic procedures is very simple with capability of being applied on pipelines, but cannot deal with uncertainties in the input data.
- DNV-101 model, as a semi-probabilistic procedure, can only estimate the standard deviation of inspection tool error and defect sizing in mitigating uncertainties.
- The degree of conservatism, as regards to the corrosion assessment is owned to safety factors introduced into the capacity equations or codes.
- The probabilistic procedures are very useful in evaluating pipeline integrity because of the inherent uncertainties associated with corrosion growth rate, inspection tools, pipeline geometry,

material properties and operating pressure.

- The pipeline probability of failure when the measured maximum defect depth is 70% of the nominal wall thickness, are: 0.94, 0.837, and 0.764 for DNV-101, B31G, and Modified B31G models respectively, using probabilistic procedures.
- On the effect of the assigned interval (epistemic uncertainty), DNV-101 and B31G models provides basically the same results while Modified B31G model still produce significant higher values of probability of failure (PoF) for lower values of measured relative corrosion defect.
- The maximum level of uncertainty that can be tolerated according to this result, for a meaningful outcome or performance is the measured maximum defect depth of about 60% through the nominal wall thickness.

Further analyses of epistemic uncertainty will be performed in the future.

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