Steel pipeline failure probability evaluation based on in-line inspection results

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1. Introduction

The main goal of this paper is to estimate onshore buried pipeline failure probability based on Magnetic Flux Leakage (MFL) inspection data. Degradation of an underground steel structures during their service life leads to reduction of the pipe wall thickness. Periodic in-line inspections are performed by grid operators to detect corrosion anomalies and size their depth, length and width. In diagnostics of steel pipelines, it is common practice to track the same flaws in different inspections (i.e. so-called defects matching) based on the longitudinal and circumferential positions of the anomalies reported by applied tools. A code-based engineering approach to estimate the failure pressure was selected as appropriate to be applied directly after in-line inspections, due to the scope of the available data, before any expansive field excavations for direct observations. Det Norske Veritas DNV-RP-F-101 analytical method of burst pressure calculation for a straight pipe was applied. A probabilistic methodology was used to evaluate the severity of part-wall external corrosion defects and their growth over time on gas transmission grid.

The Monte Carlo numerical method was selected in this paper for estimation of pipeline failure probability due to the external corrosion with respect to statistical distribution of input parameters. The predicted flaw depth growth was modeled as non-linear with a power law function parameters derived from literature [1,6,7]. The expected defect length growth rates was forecasted as linear with several scenarios. It was assumed that failure probability of an underground pipeline is influenced only by the growth of the existing features, whereas generation of new defects is neglected. The paper illustrates reliability-based maintenance planning, in the case when a number of anomalies and its statistical distributions are known from MFL in-line inspection. Criteria and formulation of a limit state function were presented to determine the burst pressure and corresponding failure probability of a pipeline DN 700, X 52 steel grade with amount of 138 fully matched single part-wall defects. The results of this study shall help maintenance engineers to solve the problems of an effective strategy in reliability-based high pressure gas pipelines management.

2. Time dependent metal loss-type defects assessment

The general corrosion of underground steel structures is mostly a consequence of electrochemical oxidation, whereas pitting corrosion is caused by either direct or alternating current at locations of the damaged coating. In the real pipeline maintenance conditions, the corrosion grow rate can be highly variable. Pitting corrosion rates have been found to be much higher than general corrosion rates. The speed of both these corrosion forms tend to be more variable in early pipeline operation time than in later maintenance years. Nevertheless, local conditions of the ground surrounding the pipe and other parameters affect the rates of corrosion, which are continuously varying along the pipeline length. The transmission pipeline can cross different types of soil over long distance. In failure calculations, a soil type would be considered as a variable or the worst case of the ground could be used [1,6,7]. From the steel pipe wall aging process point of view the type and possible damage of coating is also significant as well as detailed issues of cathodic protection system. In real maintenance conditions, the grow of external corrosion in axial direction is limited to the area of coting damage, if the insulation is strongly cohesive and is not disbanded. The studies considered in this paper are based on high resolution MFL inspections conducted in years 2000 and 2012 and defect growth rates mean values are derived from diagnostics results. The investigated pipeline was coated with bitumen and commissioned in the year 1986, which means that the diagnostics surveys were conducted not in its early service years and from this reason the electrochemical corrosion rates tend to be stable. The evaluation of the burst pressure of the pipeline as a function of operation time was computed by Monte Carlo method using reliability software called Goldsim.

A corroding high pressure steel pipeline typically fails by either small leak or burst, due to the internal gas pressure taken into consideration as only one load, mostly as random variable [2,3,5-7]. A small leak occurs if a corrosion penetrates the pipe wall prior to the plastic collapse of the remaining ligament at the defect, due to the internal pressure, whereas a burst occurs if the remaining ligament undergoes plastic collapse before the defect penetrates the pipe wall. In this study, only a pipe burst was considered because the cost of a small leak is much more insignificant compared with potential burst consequences. However, bursts can be further classified as a large leak or a rupture based on whether or not the through-wall flaw resulting from the pipe burst extends unstably in the longitudinal direction [2,3]. Flaws considered in this work have a residual wall thickness bridge before the pipe burst. Det Norske Veritas DNV-RP-F-101 [5,8] engineering approach to estimate the failure pressure is selected to be applied based on in-line inspections data, before any expansive field excavations. The time dependent failure pressure $P_{\mathrm{fDNV}}(T)$ of a corroded pipe with a single metal loss without any reinforcement is expressed as:

$$P_{\mathrm{fDNV}}(T) = \frac{2tf_u\left(1-\frac{d(T)}{t}\right)}{(D-t)\left(1-\frac{d(T)}{tQ(T)}\right)} \tag{1}$$

where bulging factor $Q(T)$ is calculated from the formula:

$$Q(T) = \sqrt{1+0.31\left(\frac{L(T)^2}{Dt}\right)} \tag{2}$$

The localized form of corrosion should be variable in time and the growth rates during maintenance period can be derived from at least two repeated inspections. A similar approach can be found in literature, e.g. [2,3,5]. The generation of new flaws between in-line inspections can be neglected. It means the assumption under which defects initiate at the same time and then grow with the mean value independently of local environmental conditions which are changeable along the pipeline length and the exact soil parameters are not well known. The paper applies a repeated in-line inspections approach to the pipe wall corrosion rate determination using the experimental mean values such as d_{mean} – for defect depth and L_{mean} – for its length. In many studies both an axial (c_L) and a radial corrosion growth (c_d) are assumed for simplicity to be constant over the forecasted period and calculated based on real diagnostics results without considering the accuracies of MFL inspection tool sizing. For a linear model of the corrosion growth applied in publications such as [3-5], an estimated defect depth $d(T)$ and its length $L(T)$ at time T is calculated as:

$$d(T) = d_{mean}(0) + c_{\mathrm{d}}\cdot T \tag{3}$$

$$L(T) = L_{mean}(0) + c_{\mathrm{L}}\cdot T \tag{4}$$

However, in the current paper, the predicted defect depth growth rate was forecasted as non-linear with a power law function [1,3,6,7] which relates to the average value of the of the corrosion velocity in depth based on inspections data performed on the studied pipeline:

$$d_p(T) = d_{mean}(0) + kT^n \tag{5}$$

where:

k - pitting proportionality and n - exponent factor are obtained in literature [1,6,7] by statistical studies. In most studies, k and n coefficients are constant and are assumed based on both variables of the pipe material properties as well as on the parameters of the surrounding ground.

Based on estimates of the corrosion growth parameters for typical soil conditions presented in [1, 6], the defects depth power low function parameters were assumed in this paper as follows:

$d_p(T) = d_{mean}(0) + 0.164 \times T^{0.78}$ (6)

A defects length growth rate in axial direction was modeled as linear according to equation (4) with following scenarios of corrosion growth rates presented in Figure 2 as a function of time:

Scenario 1 (base) - 1.8 mm/year;
Scenario 2 - 1.0 mm/year;
Scenario 3 - 0.5 mm/year;
Scenario 4 - no defects growth in axial direction.

The metal losses depths have the same corrosion growth rates values for all the considered scenarios, as shown in Figure 1. The inspections tools biases and random scattering errors as well as probability of defects detection are neglected in the current study.

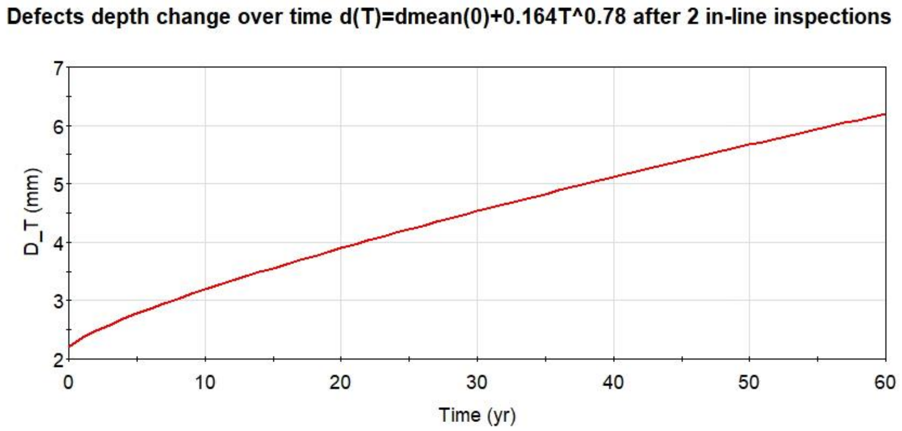
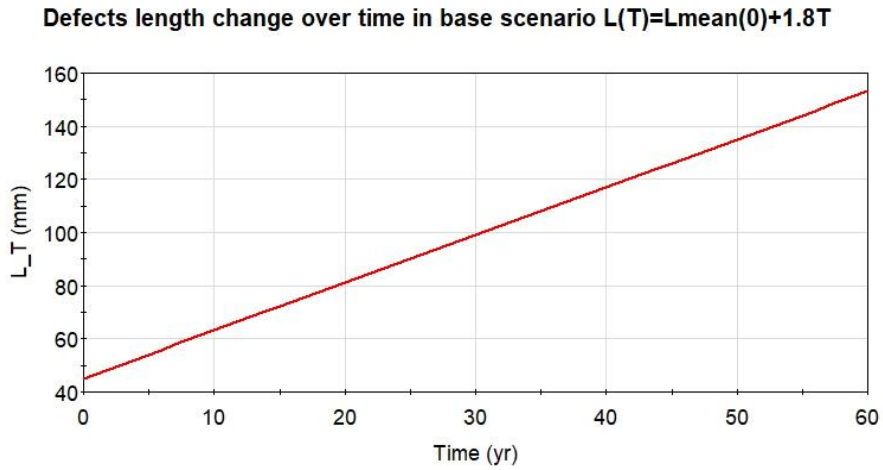


Figure 1. Defects depth growth rate over time forecasted with a power law function.



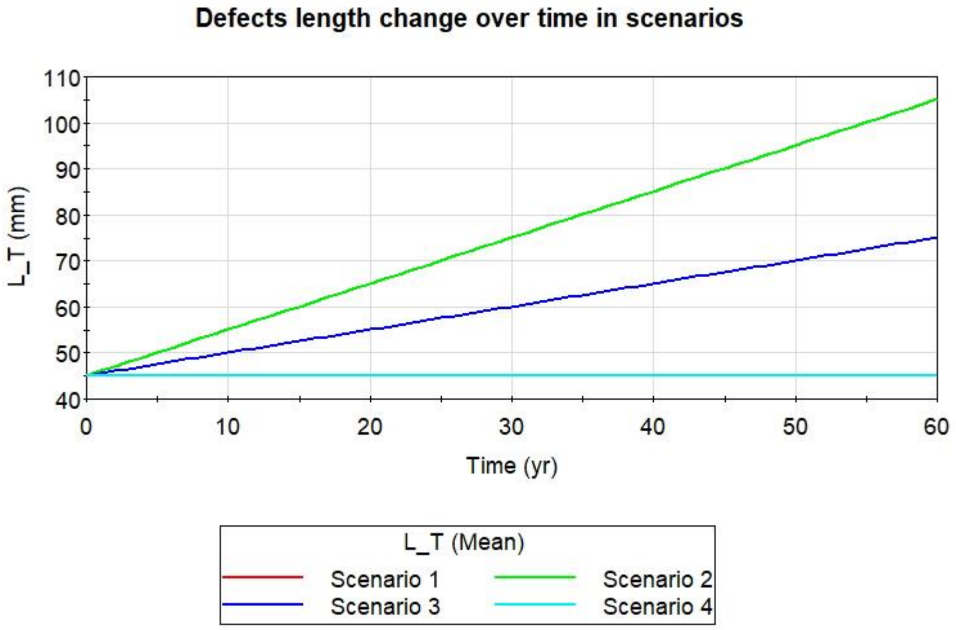


Figure 2a, 2b. Metal losses length growth rates in the axial direction for various scenarios.

2. Reliability function

A formula of a limit state function and analytical methodology based on DNV-RP-F-101 [5, 8] criteria is applied to determine the failure pressure of a pipeline with a great number of single metal losses. Similar as in publications e.g. [2-9], a pressure difference formulation of a limit state function and Monte Carlo method were applied for the reliability calculations, due to the corrosion without any pipeline extensive excavations and repairs. Limit state function $g(\vec{X})$, in the case of a pipe affected by a part-wall metal loss, can be expressed as follows:

$$g(\vec{X}) = \overrightarrow{P_{fDNV}} - \overrightarrow{OP_{max}} \tag{7}$$

where:

$\vec{P}_{fDNV}$ – vector of theoretical failure pressures;

$\overrightarrow{OP}_{max}$ – vector of maximum operating pressure of the pipeline to be applied.

Failure probability for the corroded pipe as a function of time (T) can be expressed as:

$$P_{fDNV}(T) = P[\,g(\vec{X},T) \le 0] = \int_{g(\vec{X})\le 0} f(x_i,T)\,dx_i \tag{8}$$

where:

$P_{fDNV}(T)$ – failure pressure of the corroded steel pipe as a function of time, [MPa].

The pipeline failure probability resulting from growing corrosion is determined in the current paper with the use of Monte Carlo (MC) simulation [4-9]. For a specific time period, a numerical simulation is conducted by generating random numbers for variables $\vec{P}_{fDNV}$ and $\overrightarrow{OP}_{max}$, with respect to statistical distribution of the input parameters specified in Chapter 3. For each evaluation of the limit state function (7), the occurrence of $g(\vec{X})<0$ is counted. The failure probability of the whole section of pipeline $P_{f\ pipeline}$(T) at time step T, with the assumption of independence of individual failures of pipes connected in a series is calculated as a function of time P_{ft}(T) according to formula (9):

$$P_{\text{f pipeline}}(\mathrm{T}) = 1 - \prod_{t=1}^{n}(1 - P_{ft}(T)) \tag{9}$$

where:

$$P_{ft}(T) = \frac{\mathrm{N_f}}{\mathrm{N}} \tag{10}$$

$P_{ft}(T)$ – failure probability of individual defects at time step T, [-];
n – number of corrosion anomalies based on in-line inspection data, [-];
N – total number of simulation cycles/trials, [-];
N_f – number of failure events which means simulation cycles when $g(\vec{X})<0$, [-].

For each external corrosion feature based on the in-line inspection data, the total number of failure events N_f is determined at time step T, after N samples are generated and failure probability of an individual defect can be obtained using equation (10). The smaller the probability of failure, the larger the sample size is needed in Monte Carlo method to ensure the same calculation accuracy. In this pipeline reliability study, the number of trials was set as 10^6, which is enough to ensure the accuracy of probability of failure estimation [2-4]. Computations in the current paper were carried out with Goldsim software.

3. Inputs data evaluation for reliability calculations

For the inputs parameters specified below, the pipe diameter and wall thickness are modeled as random variables based on pipe manufacturer certificates. The coefficient of variation (COV) of the random variable [X] equals the ratio between standard deviation StD[X] of the measured values and its mean value. The random variables listed below arise from the real diagnostics results. A flaws size growth rate equal the mean value obtained from the inspections data divided by whole 25 years of the pipeline service. A detailed analysis of the diagnostics results can be found in publication [5]. The choice of the Gumbel distribution for operating pressure fluctuations in this paper was based on publications [2-5,7,9]. The maximum operating pressure of studied pipeline is MOP 5.5 MPa and standard deviation computed in [5] from extreme value distribution parameter is equal to s = 0.3. Statistical distributions of all input parameters for the analyzed pipeline reliability calculations are reported in Table 1.

Table 1 – Statistical distribution of input parameters for reliability evaluation

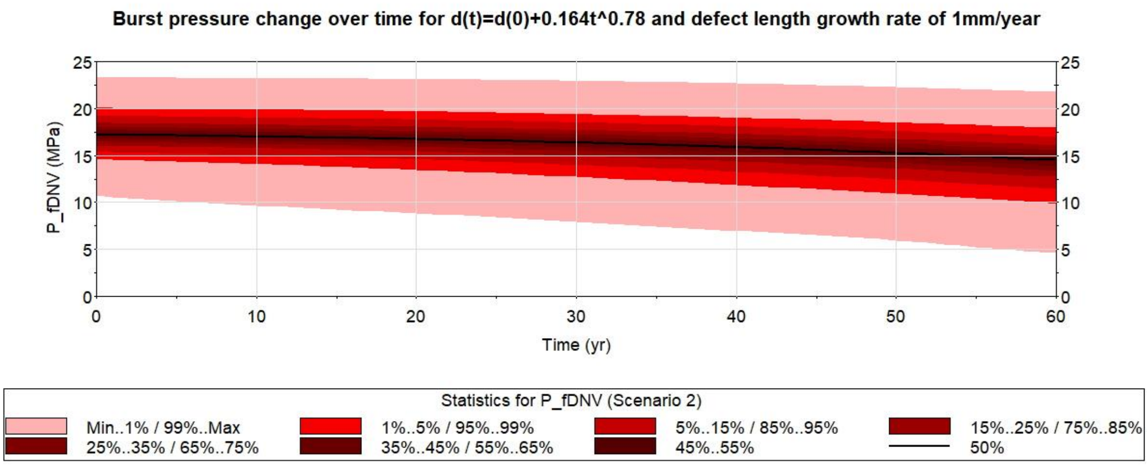
No.	Parameter	Unit	Mean value	Uncertainty Coefficients	Distribution type
1.	Steel yield strength (f_y)	MPa	370.6	StD[f_y]= 12.2 COV[f_y]= 3.3 %	Lognormal
2.	Tensile strength (f_u)	MPa	554.7	StD[f_u] = 19.4 COV[f_u]= 3.5 %	Lognormal
3.	Pipe wall thickness (t)	mm	11.0	StD[t] = 0.5 COV[t] = 4.5 %	Normal
4.	Pipe diameter (D)	mm	711.0	StD[D] = 20.3 COV[D] = 2.8 %	Normal
5.	Maximum operating pressure ($MOP=OP_{max}$)	MPa	5.5	s = 0.3 COV[MOP]= 5.5 %	Gumbel
6.	Defect depth (d)	mm	2.2	StD[d] = 0.6 COV[d] = 26.6 %	Normal
7.	Defect length (L)	mm	45.1	StD[L] = 34.6 COV[L] = 76.9 %	Lognormal

8.	Defect depth growth rate $d_p(T)$ as a power law function acc. to equation (5) with parameters n, k	mm/yr	-	-	Parameters n, k fixed/deterministic
9.	Defect length growth rate as a linear function acc. to equation (4) with parameter (c_l)	mm/yr	1.8	Scenario 1 (base) - 1.8 mm/year; Scenario 2 -1.0 mm/year; Scenario 3 -0.5 mm/year; Scenario 4 - no defects growth in the axial direction.	Fixed/deterministic

Source: Author's analysis [5]

4. Pipeline failure probability calculations

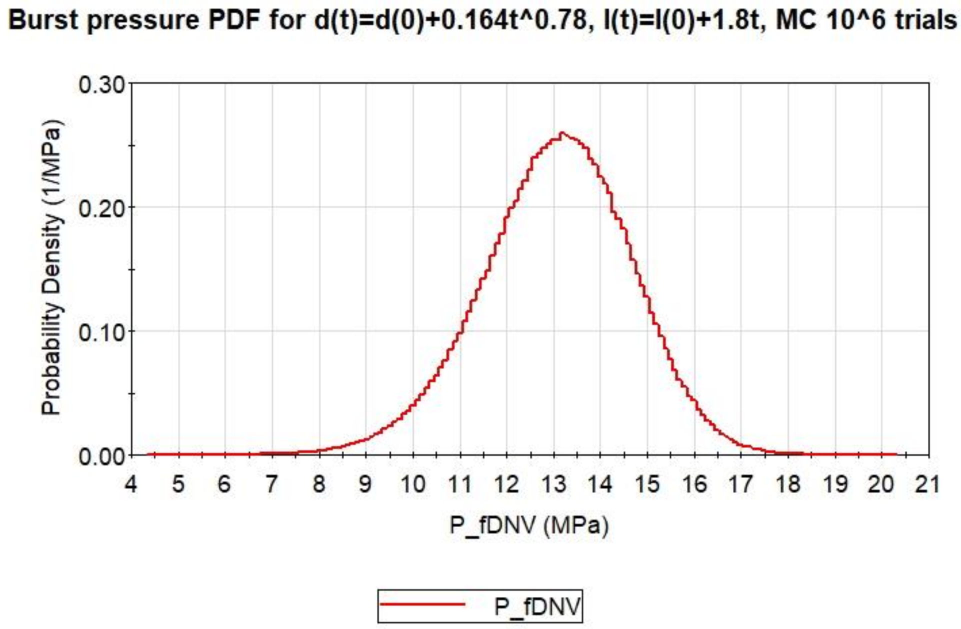
A stochastic chart of the studied pipeline failure pressure over time, due to the growth of defects dimensions $d(T)$, $L(T)$ for scenario 2 as an example, is shown in Figure 3. It can be observed that the burst pressure changes during 60 years of operations starting form the second in-line inspection decreases from 17.5 MPa to 14.5 MPa with a chance of 50%. However, there is also a 1% chance that the failure pressure at the start of pipeline operation period will be in the scope of 11÷15 MPa, and at the end of the considered pipeline life cycle period between 5 and 10 MPa, as it can be shown in Figure 3.



Source: Author's calculations.

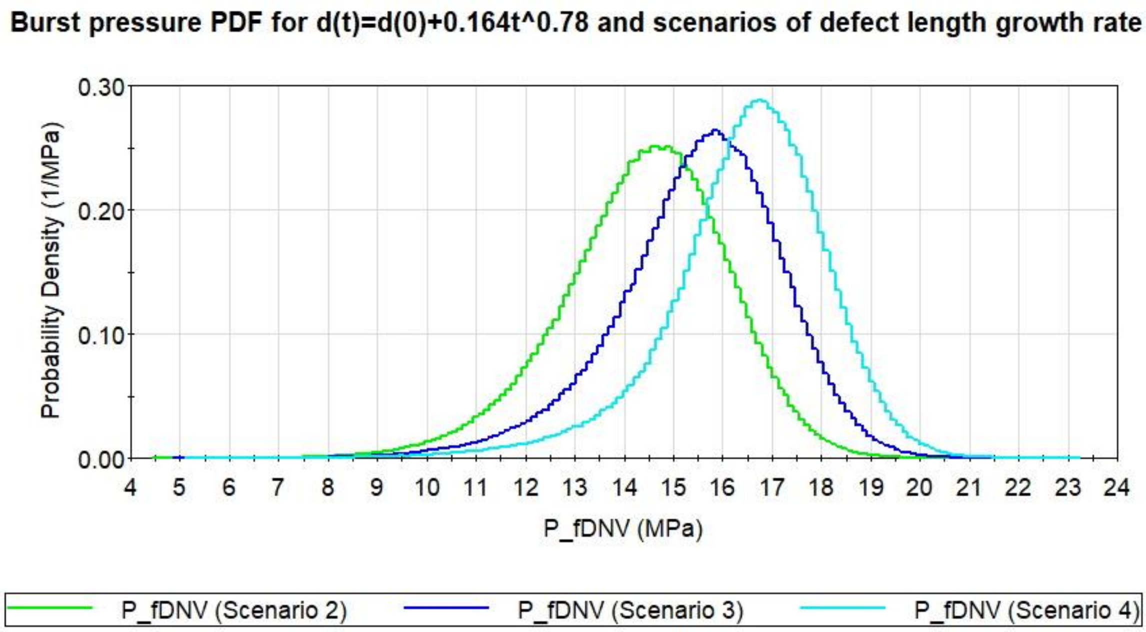
Figure 3. Stochastic burst pressure of the pipeline over time due to the growth of features dimensions $d(T)$, $L(T)$ for scenario 2.

A burst pressure probability density function for scenario 1 at the end of the considered pipeline life cycle period of 60 service years is shown in Figure 4.



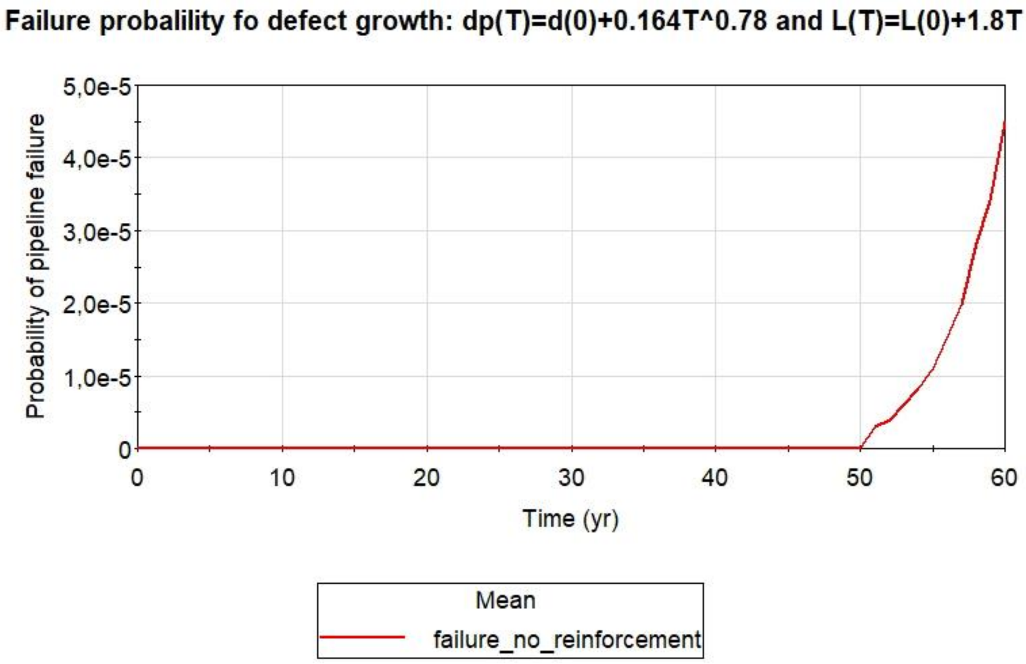
Source: Author's calculations.
Figure 4. Burst pressure probability density function for scenario 1.

For the same corrosion velocity in depth, the smaller defect length grow rates assumed for scenarios 2-4 the higher pipeline burst pressure capacities whose distributions are presented in Figure 5. For the same forecasted corrosion in depth, the overall failure probability for scenario 1 has also the highest value compare to the burst probabilities for lower corrosion growth rates in axial direction. Burst pressure change of the pipeline during the service period depends significantly on a defects length growth rate. Computations of failure pressure of the studied pipeline showed that the active pipe wall corrosion defects lie within the acceptable values for the foreseen operating conditions characterised by various parameters surveyed in the current paper.



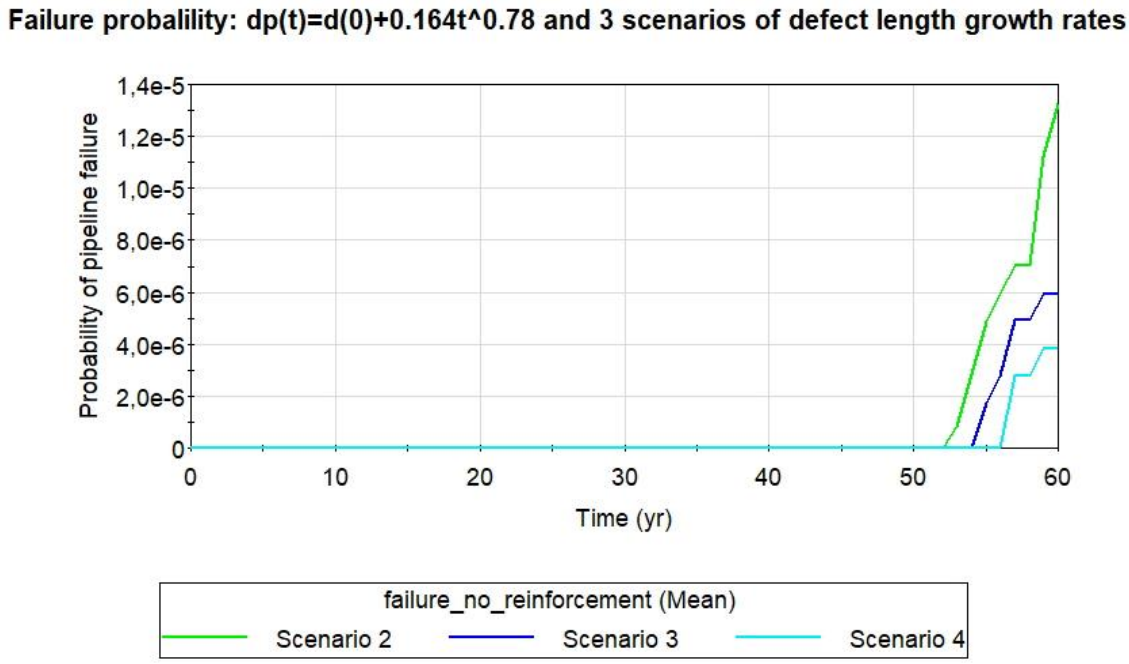
Source: Author's calculations.
Figure 5. Failure pressure probability density function for various defects length grow rates corresponding to Figure 2.

The failure probability over a life cycle of 60 years for the features depth and anomalies length considered in this paper are presented in Figures 6 and 7 as well in a logarithmic scale in Figure 8. The calculated failure probabilities over 60 years of pipeline maintenance starting from the second inspection, even for non-reinforced defected pipes, are very low and remain lower than a related code-based target value for a so-called normal safety class set in [8] as not higher than 10^{-4} per annum. For a high safety class characterised by frequent and intensive human activity in the pipeline souranding area, the target annual failure probability is set as not exeeding 10^{-5} per annum. For the studied pipeline it means that for scenario 1, after 55th year started from the second diagnostics, the most significant defects need to be repaired due to crossing the target code based probability of failure [8]. For scenario 2, the target failure probability is reached in the 59th year of pipeline operation, as it can be seen from Figures 7 and 8.



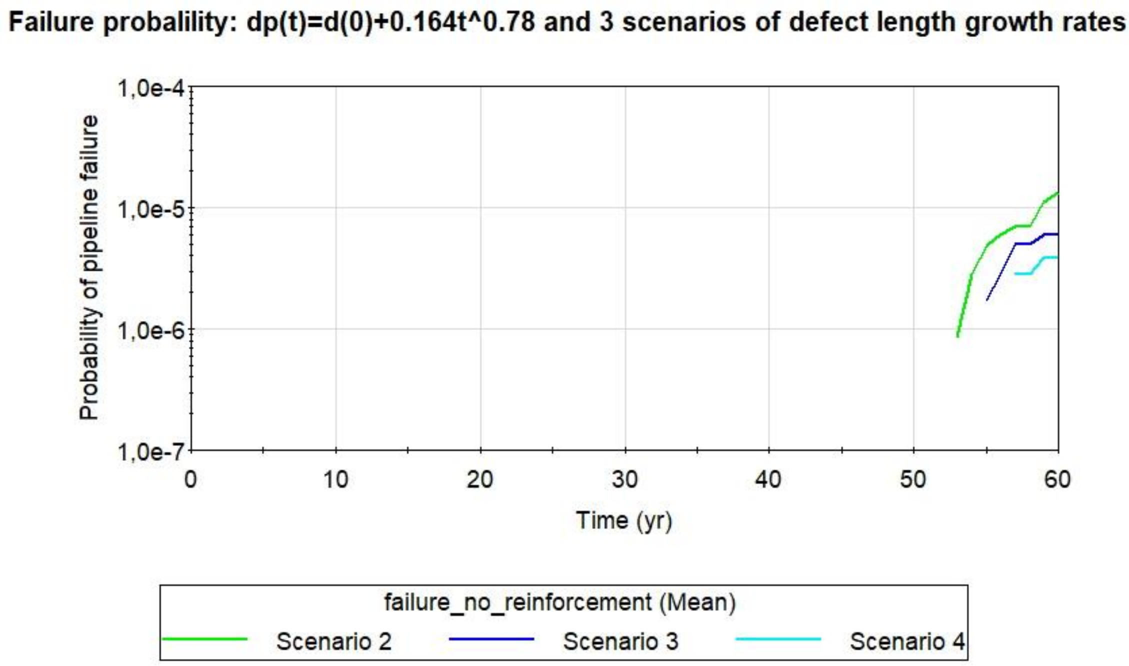
Source: Author's calculations.

Figure 6. Probability of failure over 60-year pipeline maintenance for the defects depth and their length corresponding to the base scenario.



Source: Author's calculations.

Figure 7. Probability of failure over 60-year pipeline maintenance for the feature depth and anomaly length corresponding to the data in Figure 5.



Source: Author's calculations.

Figure 8. Logarithmic chat of failure probability over 60-year pipeline maintenance for the defect depth and its length corresponding to the data in Figure 5.

5. Conclusions

Burst pressure of a steel pipeline was calculated in this paper according to DNV-RP-F101 methodology using the real two repeated diagnostic results, without any field excavations for direct assessment. For an underground gas transmission pipeline DN 700 constructed in the year 1986 from steel grade equivalent to X52, the flaws detected with MFL tools were evaluated by means of statistical methods. A burst pressure change of the pipeline during the service period depends significantly on a metal loss length growth rate as well as on the predicted defect depth increase. Computations of failure pressure of the analyzed pipeline showed that the active corrosion defects lie within the acceptable dimensions for the foreseen operating conditions characterised by various parameters survayed in the current paper.

The calculated failure probability over 60 years of pipeline service starting from the second in-line inspection, even for non-repaired defected pipes, are very low and remain lower than a related code-based target value set for a normal safety class as not higher than 10^{-4} per annum. In the later maintenance years, e.g. after studied pipeline operation life exceeding 50 years a rate of the failure probability increase is strong, which means the rapid aging process of steel underground structure.

The employed method is a technique of reliability control and extension of the remaining service life of the corroded pipelines. The applied methodology can be helpful for selection of the optimal inspection intervals for steel pipelines to maintain the failure probability within acceptable values as well as can be also used in defects repairs decisions.

6. Bibliography

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