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A risk-based inspection planning method for corroded subsea pipelines

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ABSTRACT

Risk assessment procedures for subsea projects are a key component of design and maintenance and inspection efforts, as resulting operating time may cause aging damages to adjacent subsea equipment. In particular, for subsea pipeline management work, corrosion of pipelines may impinge on a vast number of subsea pipeline systems and can result in significant environmental and financial risks, unless the appropriate management methodologies are implemented. Hence, this paper presents risk based on probability of failure (PoF) and consequence of failure (CoF) estimation of a time-variant corrosion model and burst strength for the corroded oil pipelines. The probability of corrosion defect is calculated as PoF, which is a time-variant model from measured data in the subsea industry and CoF is considered as the burst strength of corroded pipelines. Pipeline consequence modelling is performed using regulation design codes to simulate the pipeline strength and calculate the probability. The proposed methodology offers a standardised procedure for incorporating both design and inspection/maintenance planning aspects of pipeline systems, thereby providing a more systematic, comprehensive procedure for risk-based inspection than previously available.

1. Introduction

Currently, most offshore platforms are designed using risk assessment and management to reduce and mitigate the possible risks. The technology of risk assessment and management is well developed and established for the topside systems of offshore platforms. Reliability and risk assessment for subsea projects form a key component of design, and maintenance and inspection efforts, as the operating times may cause aging and damage to adjacent subsea equipment.

Subsea pipelines are used for a number of purposes in the development of subsea hydrocarbon resources, as shown in Fig. 1. A flowline system can be a single pipe pipeline system, a pipe-in-pipe system, or a bundled system. Normally, the term subsea flowlines is used to describe the subsea pipelines carrying oil and gas products from the wellhead to the riser foot. The riser is connected to the processing facilities (Bai and Bai, 2005, 2010).

Particularly for subsea pipeline management works, corrosion of pipelines can impinge on a vast number of subsea pipeline systems, resulting in significant environmental and financial risk unless the appropriate management methodologies are implemented. Therefore, it is essential to ensure that the pipeline is always running in a safe and controlled environment.

The corrosion phenomenon in the oil and gas pipeline system is a serious problem in the petroleum industry today. Previous reports (Table 1) have shown that the allocation of failure mechanisms for offshore pipelines is strongly linked to damage caused by corrosion and external loads.

Corrosion problems may occur in numerous subsystems within the offshore oil and gas production system, including the gas and oil pipelines. It is recognised as one of the most important degradation factors of pipeline metallic material and a great concern in maintaining pipeline integrity. Also, corrosion tolerance must be carefully considered in the design of a pipeline. Previous studies have assessed the importance of corrosion damage evaluation for numerous structures, including gas pipelines and offshore structures, and assessed their mathematical models (Bai and Bai, 2005, 2014; Elsayed et al., 2012; Kim et al., 2013; Kyriakides and Corona, 2007; Mohd et al., 2013).

A number of studies have been performed to predict pipeline failure in terms of its remaining strength capacity, using either a deterministic or a probabilistic approach. Sharma (2007) discusses the pipeline integrity regulation requirements (ASME B31.8S, 2014; API RP 580, 2013; API RP 1160, 2013; ASME B31G, 2009; API 1156, 1999) and how it can be best implemented to achieve reliability, sustainable profitability and regulatory compliance of pipeline systems. Those regulations are not specifically designed for subsea pipeline. A pipeline operator often uses empirical design codes such as ASME B31G, PCORRC, DNV-RP-F101 and Shell 92 for assessment (ASME B31G, 2009; Cosham and Hopkins, 2004; DNV, 2010a,

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Nomenclature

B_o	Total thickness of pipe
CoF	Consequence of failure
D	Specified outside diameter of the pipe
d	Depth of corroded region
d_0	Depth of corroded region from inspection time
d_c	Depth of corrosion
L	Length of corroded region
L_0	Length of corroded region from inspection time
M	Bulging stress magnification factor
MAOP	Maximum allowable operating pressure
$P_{(f)}$	Failure pressure of the corroded pipe
PoF	Probability of failure
Q	Length correction factor
Q_c	Length correction factor
SMTS	Specified minimum tensile strength
SMYS	Specified minimum yield strength
t	Pipe wall thickness
T	Current time
T_0	The time of last inspection
V_a	Axial corrosion rate
V_r	Radial corrosion rate
W	Corrosion width
α	Shape parameter
β	Scale parameter
γ	Location parameter
γ_d	Partial safety factor for corrosion depth
γ_m	Partial safety factor for longitudinal corrosion
σ_u	Ultimate tensile strength

2010b; Klever et al., 1995). Despite these commonly used design criteria, the predictions are known to be conservative (Belachew et al., 2009), resulting in pipelines being removed from service too early or the capacity of the pipeline being underestimated.

The regulation design codes are not fully able to predict the capacity of a pipeline as these models are based on various assumptions and simplifications that produce less accurate assessments (Oh et al., 2007). An advanced assessment method such as finite element analysis may be required to overcome such problems (Mohd et al., 2014). However, the burst strength capacity is evaluated using empirical models for simple validation in this study.

The assessment of corrosion is probabilistic in nature, with complex uncertainty (Mohd et al., 2013). Pipeline failure resulting from the reduction of burst strength capacity makes it difficult for the operator to maintain the pipeline integrity. Therefore, the serviceability of the pipeline tends to be assessed by risk-based and reliability-based fitness-for-service (FFS) assessment. Generally, for risk- and reliability-based FFS assessment of pipeline corrosion defects, risk assessment is performed to determine the pipeline target reliability. Then, using the structural reliability analysis method, the pipeline's fitness for service is evaluated by comparing pipeline retaining pressure capacity with a given maximum allowable operating pressure (MAOP). Also, Risk Based Inspection (RBI) planning is one of possible method for establishing inspection strategy based on the probabilistic risk analysis, where the inspection effort is focused on those elements with a potential to reduce the risk. RBI provides an excellent tool to evaluate the consequences and likelihood of component failure from specific degradation mechanisms and develop inspection approaches that will effectively reduce the associated risk failure. RBI is still a developing technology. American Petroleum Institute (API RP 580, 2013; API RP 1160, 2013), Det Norke Veritas (DNV, 2009, 2010a, 2010b), and American Bureau of Shipping (ABS, 2003) developed RBI methodology since 1990. Various RBI methodologies are available in the marketplace; each of them has its own merits and weaknesses (Marley et al., 2001; Bai and Bai, 2014).

However, uncertainties exist in the design parameters and wall thickness of pipeline system, which should be considered in the design as well as FFS assessment and RBI planning. In principle, RBI and reliability-based design of subsea pipelines involves the uncertainty measurements of all random variables. To work structurally with uncertainties and to provide decision support the class of uncertainty should be defined. In this reason, uncertainty can be categorised into three class: (a) parameter uncertainty as a result of the value parameters being unknown or varying, (b) model uncertainty that arises from the fact that any model is a simplification of reality, and (c) completeness uncertainty because not all contributions to risk are addressed (Abrahamsson, 2002). Considering the uncertainties are approached thorough various probability methods and expert opinions (Soares, 1997; ISO, 2006; Nodland et al., 1997; Pate-Cornell, 1996) for risk analysis.

In current industrial practice, the main objective of risk- and reliability-based FFS studies is to estimate a pipeline's present risk, define the target reliability of each pipeline segment and to determine the pressure containment capacity of the pipeline at the time it was last inspected. This approach can be used to determine and predict factors such as the remaining life capacity of the design or the remaining life to current MAOP. However, it is difficult to accurately predict the inspection planning time, including the risk level during operating time. Hence, this paper reconsiders risk based on the probability of failure (PoF) and the consequence of failure (CoF) estimation of a time-variant corrosion model and burst strength for the corroded oil pipelines. The probability of a corrosion defect is calculated as PoF, which is a time-variant model from measured data in the subsea industry, while CoF is considered as the burst strength of corroded pipelines. Pipeline consequence modelling is performed using regulation design codes to simulate the pipeline strength and calculate the probability.

The proposed methodology offers a standardised procedure for incorporating both design and inspection/maintenance planning aspects of pipeline systems, thereby providing a more systematic, comprehensive procedure for risk based inspection than previously available.

2. Methodology of inspection planning

2.1. Risk-based inspection planning methodology

The steps in the methodology proposed herein are shown in Fig. 2. The risk-based and FFS approaches are used to evaluate whether the pipeline meets the safety requirements and/or criteria. According to the acceptance criteria and safety classes, the risk form related to the pipeline management can be defined as:

2.2. Details of the methodology

2.2.1. Data gathering of subsea corroded pipelines

Corrosion can be defined as a deterioration of a metal due to chemical or electrochemical reactions between the metal and its environment. The tendency of a metal to corrode depends on a

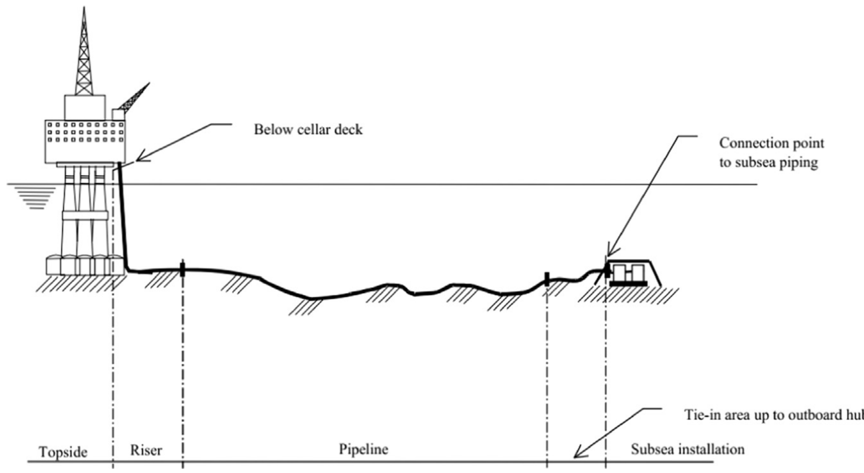


Fig. 1. Subsea pipeline (DNV, 2010a, 2010b).

given environment and the metal type (Bai and Bai, 2014). It is important to accurately predict the corrosion defects model for reliability design and qualification criteria of corroded structures.

In general, there are several corrosion defect models of mild and alloy steel for ship and offshore structures (Paik and Thayamballi, 2007). For marine pipelines internal corrosion is a major problem and slightly different from ship and offshore structures. In a subsea pipeline, various types of internal corrosion can be categorised as girth weld corrosion, massive general corrosion around the whole circumference and long plateau corrosion at about the six o'clock position. External corrosion is normally thought of as being local, covering an irregular area of the pipe, and tends to form a long groove pattern after the protective coating fails.

Therefore, corrosion defect models for data gathering consist of a proper characterisation of defects by thickness profile measurements, and an initial screening phase to decide whether detailed analysis is required. For example, a single isolated defect is based on a critical profile defined by the largest measurable characteristic dimension of the defect, and properly calibrated safety and uncertainty factors, to account for uncertainties in the assessment and thickness measurements (Mohd et al., 2013).

A schematic overview of an idealised view of the internal pitting corrosion of a pipeline is shown in Fig. 3. The corrosion defects model can be determined by three parameters, corrosion length (L), corrosion width (W) and pipeline wall thickness (t).

Pitting corrosion is the most serious type of corrosion as it may result in hazardous consequences on the risk level of corroded pipelines, such as leakage of the pipeline. Therefore, pitting corrosion can be used as a critical type of corrosion defect for data gathering of subsea corroded pipelines in this proposed method.

2.2.2. Development of risk criteria

The general acceptance criteria state the acceptable limits for the risks to human safety, the environment and the economy. The acceptance criteria are in line with the defined safety objectives of the activity.

In a risk-based inspection process, risk acceptance criteria also need to be pre-established, to compare with the results of the risk analysis and assist in decision making. The acceptance criteria are targets of risk reduction and help maintain confidence in subsea pipeline integrity. Generally, the acceptance criteria may be developed by various regulatory bodies, design codes and operators based on previous experience, design code requirements, national legislation or risk analysis (Bai and Bai, 2014; DNV, 2010a, 2010b). Risk can commonly be formulated from the quantitative risk acceptance criteria, based on the failure consequences and PoF, as shown in Table 2.

Table 1
Allocation of failure mechanisms for offshore pipelines (Parloc, 2001).

Failure mechanism	*Distribution (%)*
Corrosion	36
Material	13
External loads causing damage	38
Construction damage	2
Other	11

Accidents in subsea systems may be related to personnel, environmental or production capacity factors. The risk increases with increase in the event probability or event consequences. Alternatively, the structural failure probability requirements given in DNV-OS-F101 (Section 2) may be used as acceptance criteria, in which case no consequence assessment is required and only the failure probability needs to be established. This criterion is given per pipeline and several pipelines should be treated individually (DNV, 2010a, 2010b).

The failure of consequence should be combined with the damage evaluation to derive the failure probability. The failure probabilities are given for the whole pipeline and as such, the length of the pipeline does not determine the total failure probability of the subsea pipeline.

2.2.3. Probability of failure

Pipe failure usually takes the form of leakage, which is an initiating event resulting in serious consequences. The PoF is estimated as failure frequencies of different types of degradation mechanisms operating in the pipeline component. Generally, the failure frequency is calculated based on different damage causes such as corrosion, erosion, external impact, etc. The most critical damage reported is corrosion, as show in Table 1. Therefore, the proposed method used the corrosion defect to calculate the PoF of subsea pipelines.

Calculation of the PoF can be analysed directly using historical databases and indirectly using risk models. The most obvious advantage of the direct database method is its convenience, due to

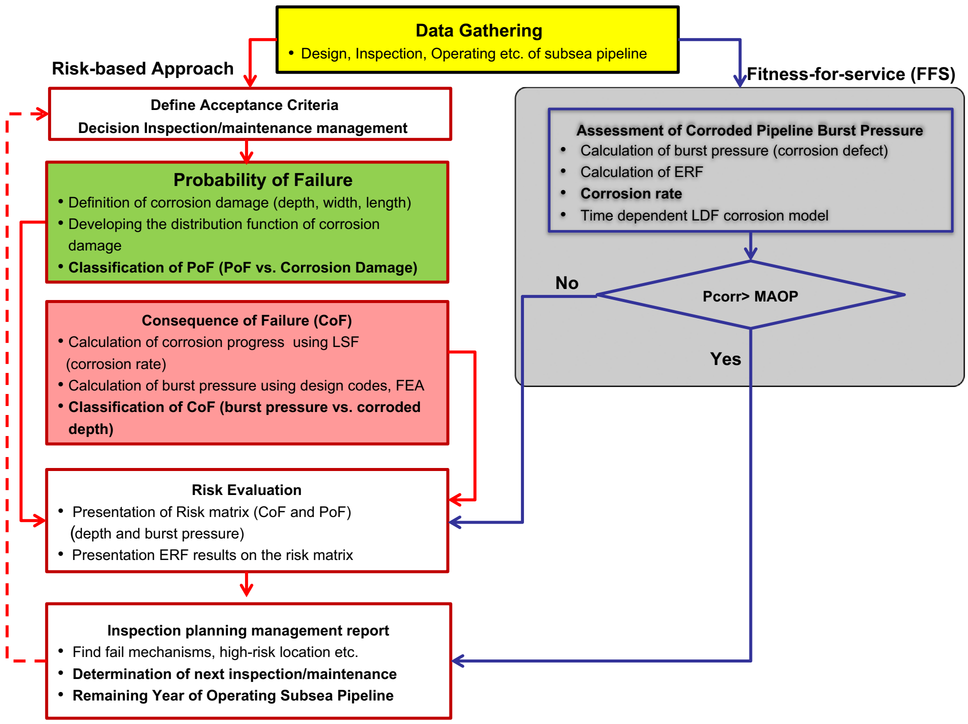


Fig. 2. Flowchart of the risk-based inspection planning method.

the use of real historical data. The reliability analysis is used to calculate the failure probability, and the main reliability calculation methods are the analytic method, the embedded method and the Monte Carlo stochastic simulation method (Rubinstein and Kroese, 2008).

In this paper, corrosion measurement data for each pipeline are collected and the relevant statistical analyses are carried out. Supposing the probability of corrosion damage (pit depth, width and length) is a random event with a frequency of N in independent initiating corrosion sampling events, the corrosion damage can be expressed as a function of time and relative frequency for each year. In addition, the relative frequency distribution of the corrosion damage can be expressed as a probability density function. Assuming some input parameters are random variables of a normal distribution function over a prolonged period of time, corrosion will occur m times in N independent samplings, and the failure probability of pipeline corrosion can be expressed by varying the probability density function.

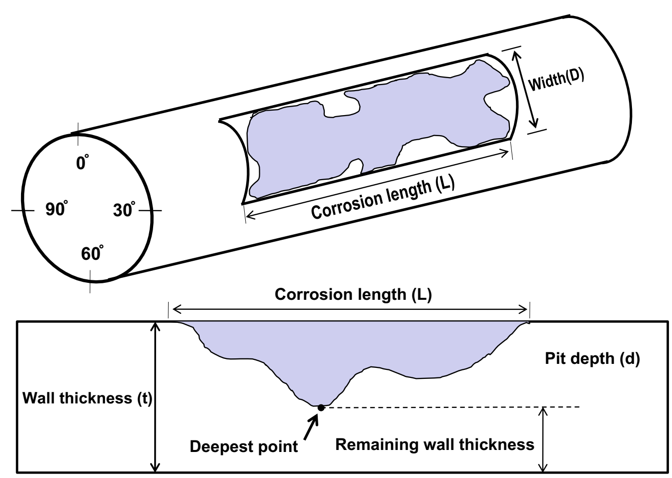


Fig. 3. Idealisation of metal loss anomaly (location and dimension) (Petronas, 2011).

2.2.4. Consequence of failure

Generally, the CoF can be expressed as the number of people affected, the amount of property damage, the extent of a spill area affected, the outage time, mission delay, money lost or any other measure of negative effects for the quantification of risk. It is usually divided into the three categories of safety, economic and environmental consequences. The factors to be analysed include the accident scenario, loads, the responses of systems and related equipment.

A critical subsea pipeline failure resulting from reduction of burst strength capacity makes it difficult for the operator to maintain and inspect the pipeline integrity. It is proposed that the defective subsea pipeline performances, in terms of burst strength capacity, are considered as CoF. This means that the burst strength capacity directly affects the CoF factors, such as property damage, the extent of a spill, etc.

In this study, the burst strength capacity is evaluated using empirical. Pipeline operators use empirical design codes such as ASME B31G, PCORRC, DNV-RP-F101 and Shell 92 in their assessment. However, it is well known that these design codes contain simplifications and assumptions that result in a less accurate assessment (Oh et al., 2007). Therefore, an advanced method of assessment, such as the finite element method, is necessary to overcome these kinds of problems. Thus, burst pressure assessment prediction by means of numerical analysis is performed using nonlinear finite element software.

The classification level of the consequence is then suggested, based on the results of the calculation of burst pressure with corrosion defect.

2.2.5. Risk evaluation

Risk assessment is used to evaluate the integrity of a pipeline system, with a view to taking action to avoid the consequences of pipeline failure. Accidents may be related to personnel, environment

Table 2
Risk raking matrix (DNV, 2010a, 2010b).

Consequence of failure Category	Environment	Economic	Human	*Probability of failure* 1	2	3	4	5
	Spillage (tonnes)	Delay/downtime	Safety	$< 10^{-5}$	10^{-4} $> 10^{-5}$	10^{-3} $> 10^{-4}$	10^{-2} $> 10^{-3}$	$> 10^{-2}$
A	~0	0 days	0					
B	< 1000	< 1 month	0.1					
C	< 10,000	1–3 months	1					
D	< 100,000	3–12 months	10					
E	> 100,000	1–3 years	100					

Table 3
General information about the target pipeline.

Pipeline data	
Type of pipeline	Crude oil pipeline, operating
Dimension (mm)	323.8
Wall thickness (mm)	12.7
Length (km)	3.87
Age (yr)	15
Material grade	API 5L X60
Max. allowable operating pressure (MAOP) (MPa)	13.1
Date pipeline was commissioned (yr)	1996
Report date	18.10.2011

or production capacity. Risk increases with the increase of event likelihood/probability or event consequences (Bai and Bai, 2014). Generally, the risk presentation can be expressed as a risk matrix, with risk acceptance criteria due to the failure consequences and probability.

$$\text{Risk} = \text{Probability of Failure (PoF)} \times \text{Consequence of Failure (CoF)} \quad (1)$$

In this paper, the risk evaluation of time-variant corroded subsea pipelines is expressed as the corrosion probability for the PoF, and the level of burst pressure for the CoF, to form a risk matrix. The distribution of the developed risk matrix can then be used to predict the risk-based inspection plan time for the lifespan of the subsea pipeline.

2.3. Consideration of uncertainty

Uncertainty can be categorised as aleatory uncertainty, epistemic uncertainty or model uncertainty. Aleatory uncertainty is the natural randomness or natural variability of a quantity, such as variability of wind or wave loading at different times. Epistemic uncertainty is the uncertainty that arises due to limited information on a quantity, such as a limited number of trials. Epistemic uncertainty also refers to uncertainty arising from an imperfect method of measuring a quantity, such as the use of faulty instruments or incorrect data due to human error. For the purpose of reliability analysis, it is important to generate sufficient data on quantities and to improve the methods used to measure quantities. Model uncertainty is usually formulated for random variables associated with either load or capacity. Model uncertainty arises due to imperfections in the mathematical model of these variables, such as the choice of probability distribution function or the imperfect estimation of the probability distribution parameters.

Our method involves both epistemic and model uncertainties in the calculation of the PoF and CoF. For example, a mathematical model with measured corrosion data that determines the CoF based on burst pressure may be a source of uncertainty. This uncertainty may be overcome though sensitivity analysis. Sensitivity analysis is an appropriate technique for assessing the magnitude of the effect of uncertainty in input data in cases where it may affect the results in terms of the final risk presentation.

However, the main objective of our paper is to reconsider risk based on the PoF and the CoF estimation of a time-variant corrosion model and burst strength for corroded oil pipelines. The proposed method of determining and expanding the PoF, CoF and risk matrix (with inspection time) offers a more systematic, comprehensive procedure for risk-based inspection than previously available. Risk assessment with uncertainties will be considered in further research work.

3. Application of the methodology

3.1. Target corroded oil pipeline

An example of a risk-based inspection planning method is given for a subsea oil export pipeline installed in 1996. Table 3 shows general information about the target pipeline, with inspection results of the corrosion defect in 2011.

3.2. Corrosion data

In practice, it is difficult to measure the corrosion of a pipeline. However, with the advancement of technology, the corrosion measurement of gas pipelines can be obtained by an internal pipeline inspection using the Magnetic Flux Leakage (MFL) intelligent pig tool.

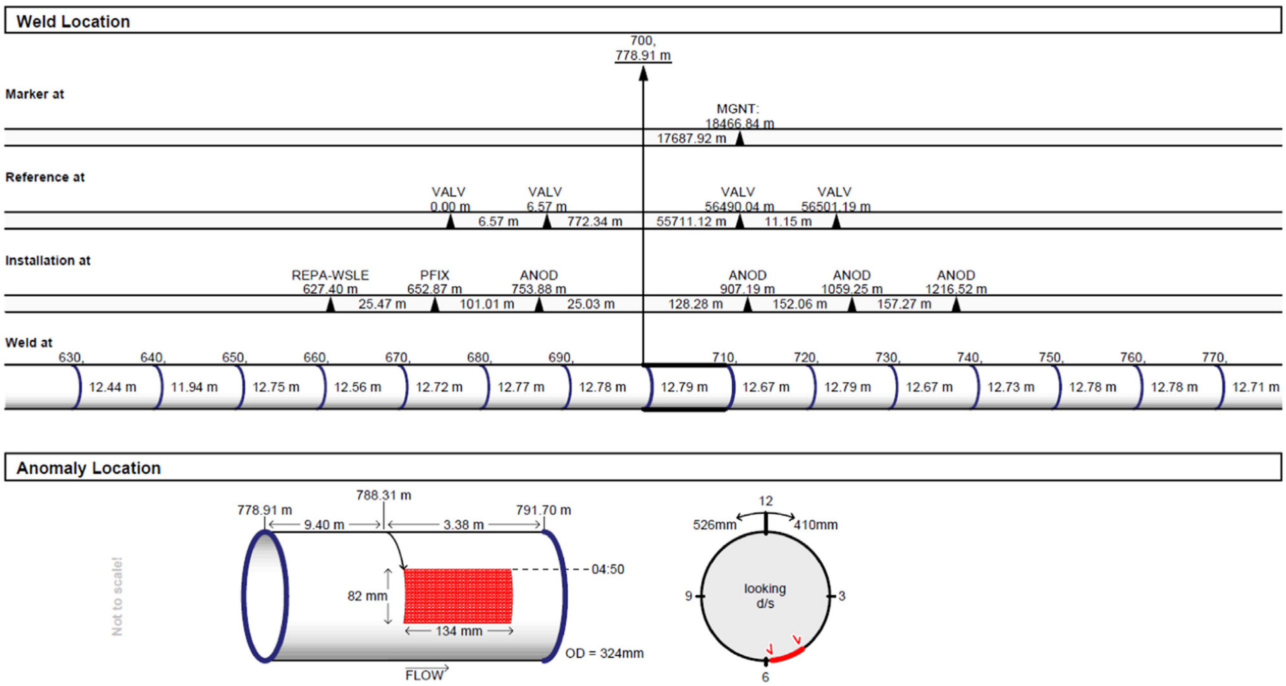


Fig. 4. Information on weld location and segment of a subsea pipeline (Petronas, 2009, 2011).

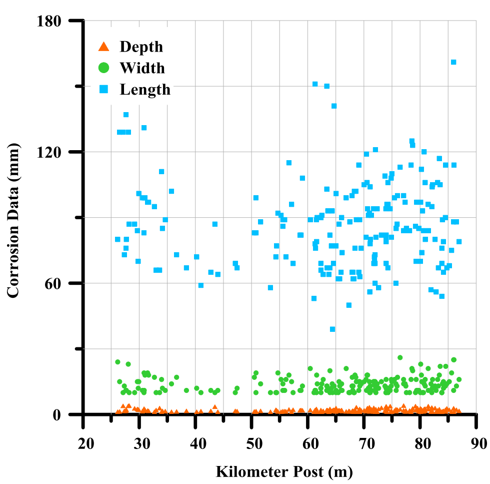


Fig. 5. Schematic view of gas pipeline corrosion.

The inspection survey is used to detect, locate, size and assess anomalies along the full length of the pipeline, which could affect the pipeline integrity for general purpose (Mohd et al., 2013). The data collected by the MFL tool were downloaded and processed for evaluation of the entire length of the pipeline, as shown in Fig. 4. Measurements of the instances and penetration depth of corrosion on the inner side of operating pipelines were collected.

A total of 1992 measurements were available for the present study, categorised as depth, width and length (Fig. 5). MFL pigging results used the defect depth and length at defect locations from actual measurement data (Petronas, 2009, 2011). Fig. 4 shows details of a subsea pipeline, such as weld location and segments and corrosion locations.

3.3. Probability of failure

The recent time-dependent pit depth corrosion model of subsea pipelines by Mohd et al. (2013) developed a comparison distribution study used to represent a corrosion model. According to their research, corrosion measurement data for each gas pipeline was collected and the relevant statistical analyses were carried out. In this study, calculation of a time-dependent corrosion model for the PoF was carried out using their relevant statistical analyses approach.

The corrosion damage (pit depth) as a function of time (pipeline age) and its relative frequency for each year can be determined using the measurement corrosion data. The distribution of the relative frequency of corrosion loss (pit depth) is scattered. Therefore, the relative frequency (probability) distribution of the corrosion damage tends to follow the Weibull distribution.

In this example, before a certain distribution function is chosen, a goodness-of-fit test is used to find the best function that can represent the overall progress of corrosion pit depth progress. A goodness-of-fit test is performed using the Anderson–Darling test statistics (Anderson and Darling, 1954) on each year's gas pipeline corrosion data, to measure how well the data follow a particular distribution.

Fig. 6 shows the typical goodness-of-fit test (Anderson-Darling) for year 15. As far as the goodness-of-fit test is concerned, the 3-parameter Weibull distribution function is a reliable distribution function to represent the corrosion characteristic of pipeline structures.

In this study, a 3-parameter Weibull function is considered as corrosion damage (pit depth) of the gas pipeline structure, as described in the previous goodness-of-fit test. The 3-parameter Weibull distribution function is formulated based on the plotted histograms. The best interval value is then used to construct histograms of pit depth corrosion against the probability density of corrosion damage. Eq. (2) shows the 3-parameter Weibull function. The plotted histograms in Fig. 7 are then used to obtain the best fit of the 3-parameter Weibull distribution function.

A continuous density function can be obtained by the best curve-fit technique, as shown in Fig. 7, given by the following 3-parameter Weibull function.

$$f(x) = \frac{\alpha}{\beta}\left(\frac{x-\gamma}{\beta}\right)^{\alpha-1} \times \exp\left[-\left(\frac{x-\gamma}{\beta}\right)^{\alpha}\right], \quad (2)$$

where $\alpha = 1.281$ (shape parameter), $\beta = 0.7987$ (scale parameter), $\gamma = 1.1$ (location parameter).

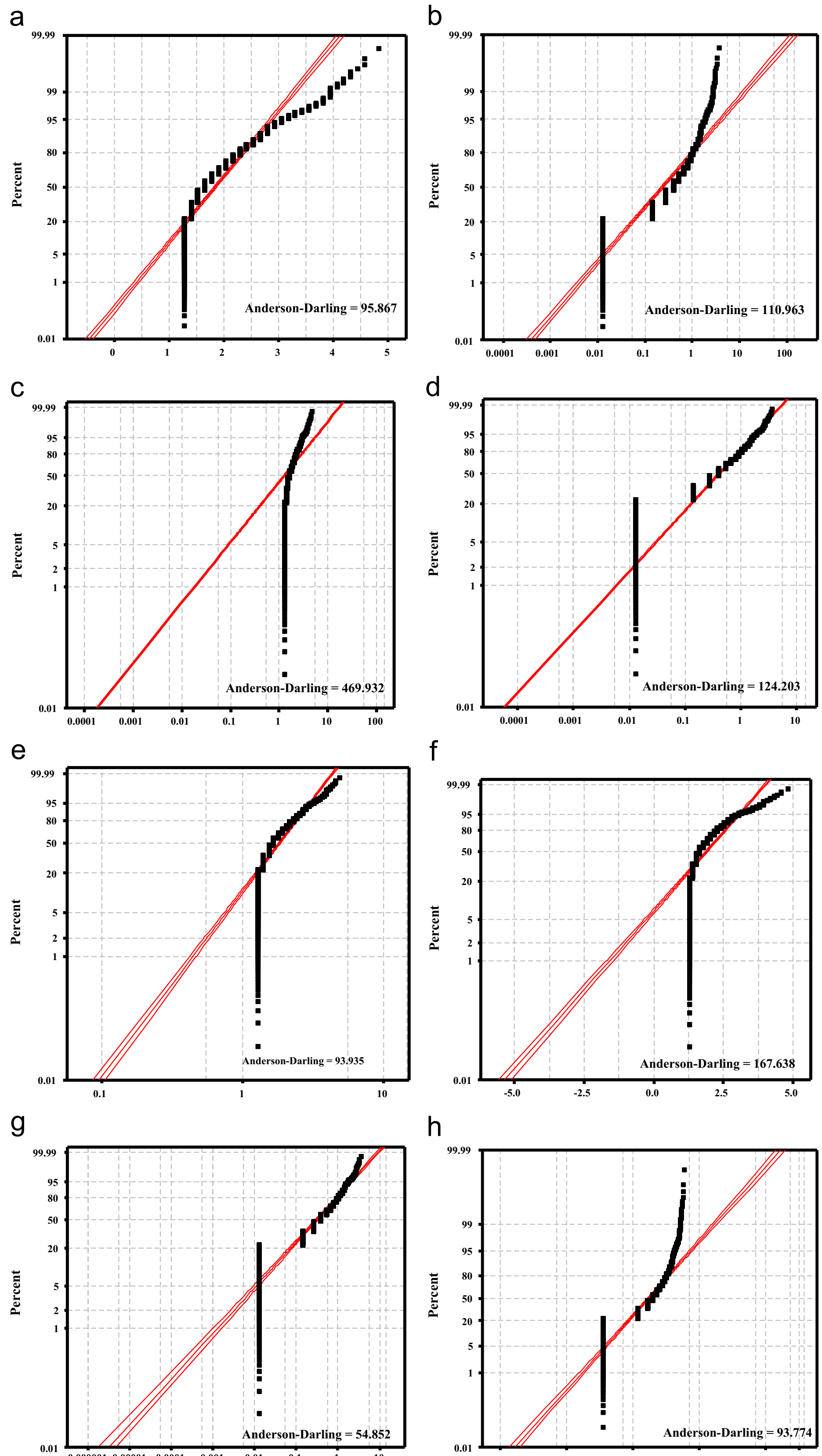


Fig. 6. Typical views for the selected distribution function goodness-of-fit-test at year 29 (95% confidence interval).

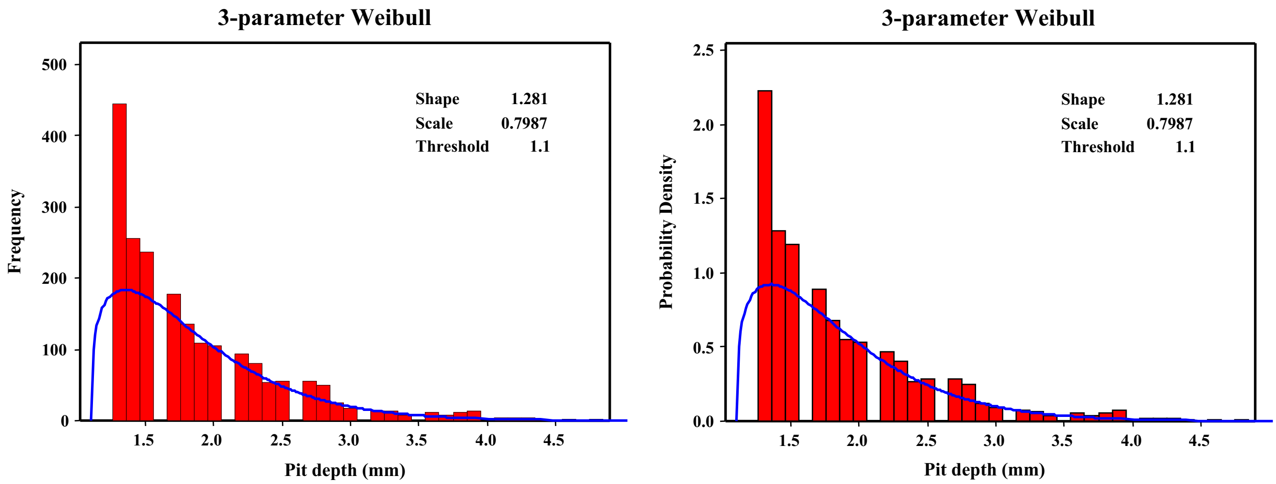


Fig. 7. Best fit of the probability density distribution for pipelines.

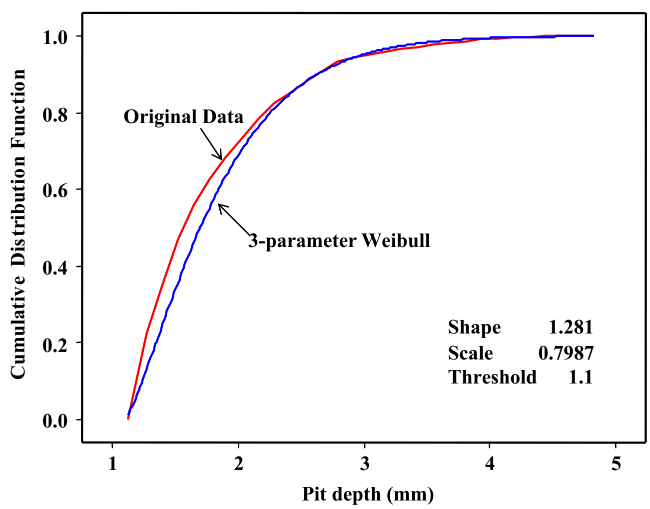


Fig. 8. Cumulative density distribution of the corrosion distribution function.

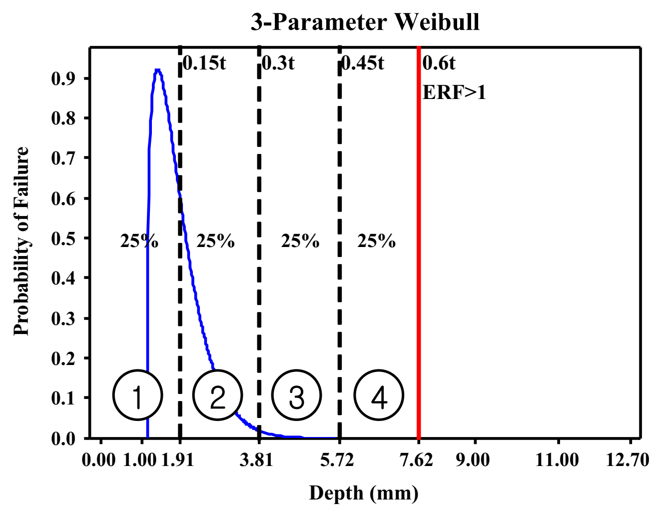


Fig. 9. Distribution of the PoF of corrosion damage (pit depth).

Fig. 8 shows the cumulative density distribution compared with the original data and the curve-fitted function, from which it can be seen that the approximate formula fits well with the original corrosion data.

According to the probability density 3-parameter Weibull function, PoF classification can be expressed as the level of depth. The ranges of corrosion depth, treated as even ranges, are shown in Fig. 9. The maximum pit depth is considered as the Estimated Repair Factor (ERF), expressed by ERF=MAOP/burst pressure. A variety of ideas and solutions regarding how to determine the range of the pit depth are considered in the discussion.

The corrosion failure probability can be expressed and classified as four levels, as shown in Table 4.

3.4. Consequence of failure

The importance of the considerations depends on the location of the pipelines and is different for offshore pipelines. Offshore pipeline consequences should consider the proximity to platforms, near-shore or landfall, environmentally sensitive fields and the cost considerations, such as repair or pigging, loss throughput, production loss and chemical injection. Therefore, the CoF can be assumed to be the burst pressure capacity considered with the corrosion defect conditions.

To obtain the burst pressure, several recently published design codes can be used (DNV, ASME B31G and Shell 92). The calculated burst pressure capacity is then compared to the value of the MAOP to ensure the safety of current corrosion defect conditions.

The time-dependent limit state function (LSF) is adopted to determine the corrosion defect size. The calculation of corrosion progress parameters (depth and length) are based on the time-dependent LSF as follows:

$$d(T) = d_0 + V_r(T - T_0)$$

$$L(T) = L_0 + V_a(T - T_0). \quad (3)$$

The radial V_r and axial V_a are the assumed corrosion rates. Generally, this step will give an approximation of the remaining life of a pipeline, based on the current defect depth. The probability of corroded pipeline failure with single or multiple corrosion defects can be approximated at any future time by applying the LSF equation.

In this study, the linear growth approximation is used, reflected by the age of the oil pipeline since it began operating over 15 years ago. It is assumed that the corrosion progress is now in the sulphate reducing bacteria (SRB) steady-state phase of Melchers model (Paik and Thayamballi, 2007). The projected integrity outputs of the defect corrosion location are calculated using the LSF

Table 4
Classification of PoF for an oil pipeline.

Classification	Depth (mm)	Description	PDF=PoF
1	$t<0.15t$	Operating safely	>0.5817
2	$0.15t\leq t<0.3t$	Operating relatively safely; stepping up monitoring	[0.5817, 0.0173]
3	$0.3t\leq t<0.45t$	Operation relatively unsafely; recent parameters need to be changed	[0.0173, 0.0002]
4	$t\geq 0.45t$	Operating in danger; recent parameters must be changed	≤ 0.002

Table 5
The calculation of corrosion progress parameters (Unit: mm).

Time		5 years		10 years		15 years		20 years		25 years		30 years	
Depth	Length	Depth	Length	Depth	Length	Depth	Length	Depth	Length	Depth	Length	Depth	Length
4.83	108.00	5.33	108.50	5.83	109.00	6.33	109.50	6.83	110.00	7.33	110.50	7.83	111.00
4.57	72.00	5.07	72.50	5.57	73.00	6.07	73.50	6.57	74.00	7.07	74.50	7.57	75.00
4.57	98.00	5.07	98.50	5.57	99.00	6.07	99.50	6.57	100.00	7.07	100.50	7.57	101.00
4.45	97.00	4.95	97.50	5.45	98.00	5.95	98.50	6.45	99.00	6.95	99.50	7.45	100.00
4.32	87.00	4.82	87.50	5.32	88.00	5.82	88.50	6.32	89.00	6.82	89.50	7.32	90.00
4.32	73.00	4.82	73.50	5.32	74.00	5.82	74.50	6.32	75.00	6.82	75.50	7.32	76.00
4.32	113.00	4.82	113.50	5.32	114.00	5.82	114.50	6.32	115.00	6.82	115.50	7.32	116.00
4.19	99.00	4.69	99.50	5.19	100.00	5.69	100.50	6.19	101.00	6.69	101.50	7.19	102.00
4.19	110.00	4.69	110.50	5.19	111.00	5.69	111.50	6.19	112.00	6.69	112.50	7.19	113.00
4.19	94.00	4.69	94.50	5.19	95.00	5.69	95.50	6.19	96.00	6.69	96.50	7.19	97.00
4.19	64	4.69	64.50	5.19	65.00	5.69	65.50	6.19	66.00	6.69	66.50	7.19	67.00
4.06	87	4.56	87.50	5.06	88.00	5.56	88.50	6.06	89.00	6.56	89.50	7.06	90.00
4.06	100	4.56	100.50	5.06	101.00	5.56	101.50	6.06	102.00	6.56	102.50	7.06	103.00
4.06	96	4.56	96.50	5.06	97.00	5.56	97.50	6.06	98.00	6.56	98.50	7.06	99.00
3.94	129	4.44	129.50	4.94	130.00	5.44	130.50	5.94	131.00	6.44	131.50	6.94	132.00
3.94	129	4.44	129.50	4.94	130.00	5.44	130.50	5.94	131.00	6.44	131.50	6.94	132.00
3.94	88	4.44	88.50	4.94	89.00	5.44	89.50	5.94	90.00	6.44	90.50	6.94	91.00
3.94	99	4.44	99.50	4.94	100.00	5.44	100.50	5.94	101.00	6.44	101.50	6.94	102.00
3.94	142	4.44	142.50	4.94	143.00	5.44	143.50	5.94	144.00	6.44	144.50	6.94	145.00
3.94	74	4.44	74.50	4.94	75.00	5.44	75.50	5.94	76.00	6.44	76.50	6.94	77.00
3.94	102	4.44	102.50	4.94	103.00	5.44	103.50	5.94	104.00	6.44	104.50	6.94	105.00
3.94	100	4.44	100.50	4.94	101.00	5.44	101.50	5.94	102.00	6.44	102.50	6.94	103.00
3.94	109	4.44	109.50	4.94	110.00	5.44	110.50	5.94	111.00	6.44	111.50	6.94	112.00
3.94	135	4.44	135.50	4.94	136.00	5.44	136.50	5.94	137.00	6.44	137.50	6.94	138.00
3.94	54	4.44	54.50	4.94	55.00	5.44	55.50	5.94	56.00	6.44	56.50	6.94	57.00
3.94	66	4.44	66.50	4.94	67.00	5.44	67.50	5.94	68.00	6.44	68.50	6.94	69.00
3.94	81	4.44	81.50	4.94	82.00	5.44	82.50	5.94	83.00	6.44	83.50	6.94	84.00
3.94	66	4.44	66.50	4.94	67.00	5.44	67.50	5.94	68.00	6.44	68.50	6.94	69.00
3.81	94	4.31	94.50	4.81	95.00	5.31	95.50	5.81	96.00	6.31	96.50	6.81	97.00
3.81	86	4.31	86.50	4.81	87.00	5.31	87.50	5.81	88.00	6.31	88.50	6.81	89.00
3.81	84	4.31	84.50	4.81	85.00	5.31	85.50	5.81	86.00	6.31	86.50	6.81	87.00
3.81	89	4.31	89.50	4.81	90.00	5.31	90.50	5.81	91.00	6.31	91.50	6.81	92.00
3.81	97	4.31	97.50	4.81	98.00	5.31	98.50	5.81	99.00	6.31	99.50	6.81	100.00
3.81	126	4.31	126.50	4.81	127.00	5.31	127.50	5.81	128.00	6.31	128.50	6.81	129.00
3.81	96	4.31	96.50	4.81	97.00	5.31	97.50	5.81	98.00	6.31	98.50	6.81	99.00
3.81	75	4.31	75.50	4.81	76.00	5.31	76.50	5.81	77.00	6.31	77.50	6.81	78.00
3.81	146	4.31	146.50	4.81	147.00	5.31	147.50	5.81	148.00	6.31	148.50	6.81	149.00
3.81	83	4.31	83.50	4.81	84.00	5.31	84.50	5.81	85.00	6.31	85.50	6.81	86.00
3.81	69	4.31	69.50	4.81	70.00	5.31	70.50	5.81	71.00	6.31	71.50	6.81	72.00

equation and listed in Table 5. The defect depth and length of a single corrosion defect increase linearly over time.

3.4.1. *Predicted burst pressure by design code*

Pipeline operators use empirical design codes such as DNV RP F101, ASME B31G, BS 7910 PCORRC, DNV-RP-F101 and Shell 92 in their assessments. The details of failure pressure expression and corrosion defect shape are shown in Table 6.

3.4.2. *Results of burst pressure*

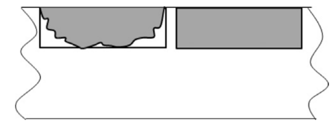
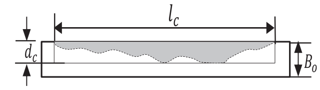
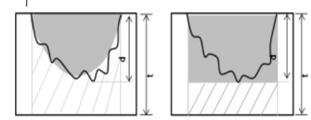
The measured corrosion data, with the LSF equation, are used to calculate the defective pipeline's burst pressure capacity. There are hundreds of defect locations in the target pipeline. However, for our purposes, only severe defect depth is selected and analysed. As a consequence, 39 defect locations, which are the most serious cases, are selected. The calculation of the burst pressure of the defect corroded pipeline is calculated by design codes.

The burst pressure results for severe defect points are shown in Fig. 10 and listed in Table 6. It can be seen that at an individual defect depth, the prediction of burst pressure varies between each design code. The Shell 92 code gives the lowest burst pressure prediction compared to the other codes. In particular, the DNV-RP-F101 code and BS 7910 codes show similar results.

3.4.3. *Remaining lifespan of the subsea pipeline*

The remaining life of an ongoing subsea pipeline can be calculated using the LSF equation, as described in Eq. (3). The corrosion rate constant value is taken as 0.1 mm/year, reflecting the pipeline inspection report (Petronas, 2011). The projected integrity outputs of the defect corrosion location are then calculated using the LSF equation and listed in Table 5. Fig. 11 shows the

Table 6
Methods of burst pressure by design code.

Code	Expression	Defect shape
DNV RP F101	$P_f = r_m \times \text{SMTS} \times \left(\frac{2t}{D-t}\right) \times \left(\frac{1-\lambda_d\left(\frac{d}{t}\right)}{1-\lambda_d\frac{1}{Q}\left(\frac{d}{t}\right)}\right)$	
BS 7910	$P_f = \frac{2B_O\sigma_u}{(D-B_O)} \times \frac{\left(1-\frac{d_c}{B_O}\right)}{\left(1-\frac{d_c}{B_O}\frac{1}{Q_c}\right)}$	
ASME B31G	$P_f = \text{SMTS} + 69.1\ \text{MPa}\frac{2t}{D}\left(\frac{1-0.85\frac{d}{t}}{1-0.85\frac{1}{M}\frac{d}{t}}\right)$	
PCORRC	$P_f = 0.95\sigma_{u.Test} \times \left(\frac{2t}{D}\right) \times \left(1-\frac{d}{t} \times \left(1-e^{-0.224\frac{L}{\sqrt{\frac{D}{2}(t-d)}}}\right)\right)$	Rectangular
SHELL92	$P_f = 1.8\sigma_u\frac{2t}{D}\left(\frac{1-\frac{d}{t}}{1-\frac{d}{t}M^{-1}}\right)$	Rectangular

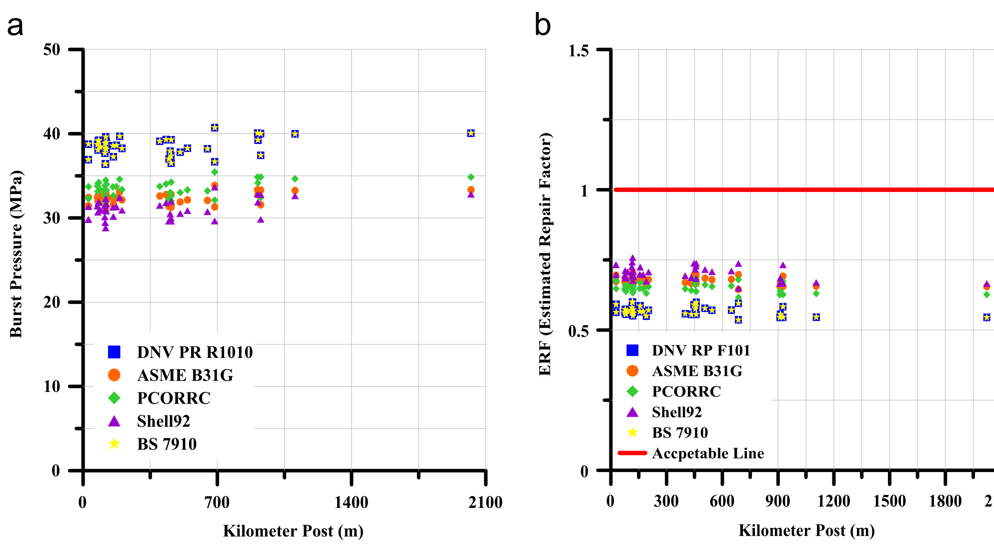


Fig. 10. Burst pressure (a) and ERF (b) results along the pipeline.

ERF results of the Shell 92 design code along the pipeline for the project integrity assessment. The results show that this pipeline needs to be repaired before 2041 and the burst is located at 117.56 m.

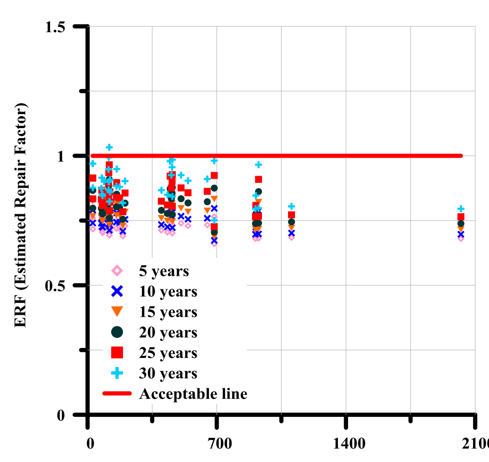


Fig. 11. ERF results of the Shell 92 code along the pipeline.

3.4.4. Determination of CoF based on burst pressure.

Classification of the level of consequence is based on the results of the calculation of burst pressure with corrosion defect. To determine the range of burst pressure, it can be categorised with corroded depth from the calculation of corrosion progress parameters (depth and length) as shown in Table 7. In this paper, the corroded depth is assumed as 0.15t interval corroded depth, as shown in Table 8. According to this range of corroded depth, the range of burst pressure can be identified automatically for classification of CoF based on burst pressure.

Table 9 shows the classification of the CoF based on burst pressure. Generally, the safety class definition is based on the fluid

Table 7
Result for burst pressure by design codes.

Depth (mm)	*Length* (mm)	*Burst pressure* (MPa)				
		DNV	ASME	PCORRC	SHELL92	BS7910
4.83	108	36.42	30.94	31.50	28.80	36.42
4.57	72	39.11	32.61	33.74	31.48	39.11
4.57	98	37.44	31.56	32.42	29.82	37.44
4.45	97	37.68	31.72	32.67	30.11	37.68
4.32	87	38.45	32.20	33.34	30.90	38.45
4.32	73	39.31	32.76	34.03	31.79	39.31
4.32	113	37.00	31.37	32.20	29.61	37.00
4.19	99	37.94	31.92	33.00	30.49	37.94
4.19	110	37.36	31.59	32.55	29.99	37.36
4.19	94	38.22	32.08	33.21	30.74	38.22
4.19	64	39.98	33.25	34.65	32.61	39.98
4.06	87	38.77	32.43	33.71	31.33	38.77
4.06	100	38.07	32.01	33.16	30.67	38.07
4.06	96	38.28	32.14	33.33	30.86	38.28
3.94	129	36.92	31.43	32.32	29.81	36.92
3.94	129	36.92	31.43	32.32	29.81	36.92
3.94	88	38.87	32.52	33.86	31.48	38.87
3.94	99	38.30	32.17	33.41	30.95	38.30
3.94	142	36.40	31.18	31.90	29.43	36.40
3.94	74	39.63	33.02	34.47	32.28	39.63
3.94	102	38.15	32.09	33.29	30.81	38.15
3.94	100	38.25	32.14	33.37	30.90	38.25
3.94	109	37.81	31.89	33.02	30.52	37.81
3.94	135	36.67	31.31	32.12	29.63	36.67
3.94	54	40.73	33.86	35.45	33.66	40.73
3.94	66	40.07	33.34	34.85	32.80	40.07
3.94	81	39.25	32.76	34.16	31.87	39.25
3.94	66	40.07	33.34	34.85	32.80	40.07
3.81	94	38.72	32.44	33.80	31.40	38.72
3.81	86	39.12	32.70	34.12	31.79	39.12
3.81	84	39.23	32.76	34.21	31.90	39.23
3.81	89	38.97	32.60	34.00	31.64	38.97
3.81	97	38.57	32.36	33.68	31.26	38.57
3.81	126	37.26	31.64	32.65	30.16	37.26
3.81	96	38.62	32.39	33.72	31.31	38.62
3.81	75	39.70	33.08	34.59	32.40	39.70
3.81	146	36.50	31.27	32.04	29.60	36.50
3.81	83	39.28	32.80	34.25	31.95	39.28
3.81	69	40.02	33.31	34.86	32.77	40.02

Table 8
Summary of corrosion damage and burst pressure by design code (Shell 92).

	Corroded depth (mm)	*Ave. length* (mm)	*Ave. width* (mm)	*Burst pressure* (MPa)
1	0.15t	218	14	32.7345
2	0.30t	218	14	28.3475
3	0.45t	218	14	23.4836

Table 9
Classification of the CoF based on burst pressure.

	Class	*Burst pressure*	*Description*
A	Low	$P > 32.7345$	Regular inspection
B	Normal	$32.7345 \geq P > 28.3475$	Always pay attention to structure
C	High	$28.3475 \geq P > 23.4836$	Need to discuss the maintenance time
D	Very high	$P \leq 23.4836$	Operation terminated and maintenance

categories and pipeline location. However, it may be difficult to identify the consequence level for quantitative spillage, delay time and safety in the first inspection stage, with only corrosion uncertainty. Therefore, the determination of class and description is based on the international code (ISO, 2006).

There are a variety of ideas and solutions regarding how to determine the ranges using analytical, statistical, numerical methods and/or judgement of past experience. The details and discussion of assumptions and propositions are further discussed in the next section.

3.5. Risk evaluation and inspection planning

The risk assessment is used to evaluate the integrity of a pipeline system, with a view to taking action to avoid the consequences of pipeline failure. According to the accepted criteria and safety classes, the risk related to the pipeline operation is defined by multiplying the PoF by the CoF.

In this paper, determination of the PoF class is calculated by corrosion defects expressed as the probability density function analysis, while the CoF class is calculated to focus on burst pressure using design codes, as shown in Tables 4 and 9.

The results can be expressed as a risk matrix, which shows the risk acceptance criteria due to the failure consequences and probability of corroded oil pipeline, as shown in Fig. 12. The CoF and the PoF class are presented as a range (A–D classes) of burst pressure in the horizontal direction and a range (1–4 classes) of corrosion damage in the vertical direction.

To predict the inspection and maintenance time, the time-dependent LSF is used to calculate the burst pressure and corrosion depth to operating time on the risk matrix form (Fig. 12). Table 10 shows the predicted inspection planning results, with maximum depth along with installation year. The first inspection year (2011) is between the acceptable and unacceptable levels. Between 2016 and 2039, it is at the unacceptable level, as shown in Fig. 9.

These results can be used to propose and plan the inspection times and periods of the target oil pipeline at the design stage and/or at the first inspection period.

3.6. Discussion

Risk-based inspection (RBI) is a means to design and optimise an inspection scheme based on the performance of a risk assessment program, using a historical database and experience and engineering judgement (Bai and Bai, 2014).

Subsea pipeline failure resulting from reduction of the burst strength capacity makes it difficult for operators to maintain the pipeline integrity. Therefore, the serviceability of the pipeline should be assessed by means of a fitness-for-service (FFS) assessment. The FFS is an engineering assessment of pipeline defects using established defect assessment methodologies. In this paper, we reconsider the risk assessment and FFS methodologies based on the PoF and CoF estimation of a time-variant corrosion model and burst strength for risk-based inspection planning of the corroded oil pipelines.

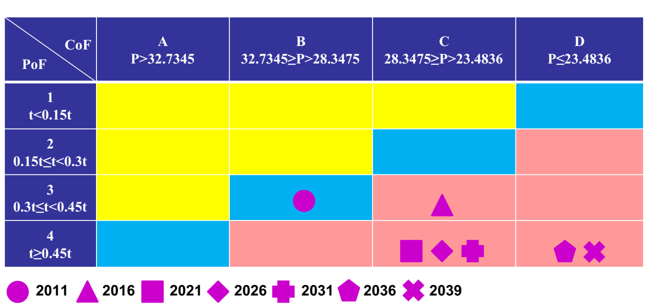


Fig. 12. ERF results of the Shell 92 code along the pipeline.

The PoF was assumed as corrosion damage (pit depth), using the probability density function of the first inspection measurement of corrosion data. It may happen that definition and classification of the PoF class and general PoF of subsea pipelines varies. However, it can provide methodologies for accurate inspection/maintenance planning based on limited information, such as measurement data without a qualitative historical database and experience and engineering judgement. The PoF is presented in Table 4 and Fig. 9. Discussion is needed on how to determine the range of pit depth. This simplified approach is used to determine the range, and validation can be carried out to verify this classification method.

Pipeline consequence modelling is performed using regulation design codes to simulate the pipeline strength and calculate the probability. Generally, PoF calculation gives sufficient information for the management of subsea pipelines in industrial practice. The burst pressure was used to determine the CoF. Burst pressure is the most critical structural strength capacity of subsea pipelines due to oil/gas spillage and delays in terms of consequence failures. Similar to the presentation of the PoF, the CoF is needed to determine the range of burst pressure according to pit depth. We used a simplified approach to determine the range.

The calculation of burst pressure only used some regulation design codes, such as Shell 92, which gives burst pressure due to the effect of corrosion damage. It would be useful to simulate FEA to validate and verify the results.

The risk presentation uses a risk matrix form, which is not a general risk matrix. However, it can accurately estimate the time and the tendency of the subsea pipeline to decrease capacity with corrosion rate, operating time and the effect of corrosion damage. Many assumptions and simplified approaches and methodologies are used. However, it would be useful to develop a standardised procedure for inspection/maintenance planning of subsea pipelines.

The many sources of uncertainty for any risk assessment for oil spill, fire or explosion hazards can be categorised by the source term, estimation of the hazardous envelope by mathematical consequence models, the establishment of target vulnerability and the estimation of likelihood (HSE, 2006). The greatest source of inaccuracy or uncertainty in any risk assessment is usually associated with whether any hazards have been missed during hazard identification. Generally, a risk assessment ranks risk for the consideration of further risk reduction. A key issue in the integrity of a risk assessment is therefore whether any events that would have been given a high risk ranking have been missed from the scope. According to an HSE Information sheet (HSE, 2006), where consultants or contractors are employed to carry out a risk assessment, their scope of work is expected to include the making of recommendations about the potential for further risk reduction. The duty holder is responsible for the evaluation of these recommendations. A way of dealing with uncertainties in event frequencies is to use standardised numbers, usually based on generic data.

Table 10
Prediction of inspection planning based on risk evaluation.

Year	*Maximum depth* (mm)	*Percent* (%)	*Installation year*
2011	4.83	0.38	15
2016	5.33	0.42	20
2021	5.83	0.46	25
2026	6.33	0.49	31
2031	6.83	0.54	35
2036	7.33	0.58	40
2039	7.63	0.60	43

Any uncertainty in the inputs to the frequency analysis can be addressed by conservative assumptions.

In the risk-based inspection planning method, subsea pipelines/riser systems are periodically inspected to check their integrity. The inspection data, when combined with the uncertainties highlighted earlier and implemented in a probabilistic framework, provide a rational basis for assessing the reliability of these structures. In determining the reliability of a pipeline against a given uncertainty, the random variables that conveniently define the uncertainty are modelled using a corresponding probability distribution function. The probability distribution function can be developed based on the analysis of record data, inspection data and theoretical observations.

Uncertainty can be categorised as aleatory uncertainty, epistemic uncertainty or model uncertainty. Aleatory uncertainty is the natural randomness or natural variability of a quantity, such as variability of wind or wave loading at different times. Epistemic uncertainty is the uncertainty that arises due to limited information on a quantity, such as a limited number of trials. Epistemic uncertainty also refers to uncertainty arising from an imperfect method of measuring a quantity, such as the use of faulty instruments or incorrect data due to human error. For the purpose of reliability analysis, it is important to generate sufficient data on quantities and to improve the methods used to measure quantities. Model uncertainty is usually formulated for random variables associated with either load or capacity. Model uncertainty arises due to imperfections in the mathematical model of these variables, such as the choice of probability distribution function or the imperfect estimation of the probability distribution parameters.

Our method involves both epistemic and model uncertainties in the calculation of the PoF and CoF. For example, a mathematical model with measured corrosion data that determines the CoF based on burst pressure may be a source of uncertainty. This uncertainty may be overcome though sensitivity analysis. Sensitivity analysis is an appropriate technique for assessing the magnitude of the effect of uncertainty in input data in cases where it may affect the results in terms of the final risk presentation.

However, the main objective of our paper is to reconsider risk based on the PoF and the CoF estimation of a time-variant corrosion model and burst strength for corroded oil pipelines. The proposed method of determining and expanding the PoF, CoF and risk matrix (with inspection time) offers a more systematic, comprehensive procedure for risk-based inspection than previously available. Risk assessment with uncertainties may be discussed in further research work.

4. Conclusion and remarks

The proposed methodology offers a standardised procedure for incorporating both design and inspection/maintenance planning aspects of pipeline systems, thereby providing a more systematic, comprehensive procedure for risk based inspection than previously available.

In current industrial practice, the main objective of risk- and reliability-based FFS studies is to estimate a pipeline's current risk, define the target reliability of each pipeline segment and determine the pressure containment capacity of the pipeline at the time it was last inspected.

This approach can be used to determine and predict factors such as the remaining life capacity of the design or the remaining life to current maximum allowable operating pressure (MAOP). Generally, for risk- and reliability-based FFS assessments of pipeline corrosion defects, risk assessment is performed to determine the pipeline target reliability. Then, using the structural reliability analysis method, the pipeline's fitness for service is evaluated by comparing its retaining pressure capacity with a given MAOP.

However, it is difficult to accurately predict the inspection planning time, including the risk level during operating time. Further, no exact presentations of inspection planning time currently exist. This paper reconsiders risk based on the probability of failure (PoF) and the consequence of failure (CoF) estimation of a time-variant corrosion model and burst strength for corroded oil pipelines. The probability of a corrosion defect is calculated as a PoF using a time-variant model derived from measured data in the subsea industry, whereas the CoF is considered to be the burst strength of corroded pipelines. Pipeline consequence modelling is performed using regulation design codes to simulate the pipeline strength and calculate the PoF.

The proposed method is both a good way of calculating the PoF of a corroded pipeline and of classifying the PoF. The method is easy to execute and can be meaningful for determining the risk level and sufficient PoF of pipelines with corrosion defects. The proposed method of determining the PoF, CoF and risk matrix (with inspection time) can be used to inform and offer a standardised procedure for incorporating both design and inspection/maintenance planning aspects of pipeline systems, thereby providing a more systematic, comprehensive procedure for risk-based inspection than previously available.

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