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# DETERMINISTIC PREDICTION OF CORRODING PIPELINE REMAINING STRENGTH IN MARINE ENVIRONMENT USING DNV RP –F101 (PART A)

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**Abstract:** Internal corrosion has long been acknowledged as one of the dominant forms of deterioration process that contribute to the containment loss for marine steel pipelines. Aging and deteriorating pipelines under influence of corrosion threat may experience a serious reduction of their structural integrity and can lead to eventual failure. To secure pipeline safety for a long and profitable life, the operators need to develop their own risk-based inspection schedule for future inspection and maintenance activities. A deterministic methodology for predicting the remaining strength of submarine pipelines subjected to internal corrosion using a capacity equation as included in the DNV RP-F101 (*Part A*) code is described in this paper. The equation can be used to estimate the maximum allowable operating pressure of the corroding pipelines based on a series of pigging data, which represents the corrosion pit location and dimension. The introduction of partial safety factors in the *Part A* of the DNV RP-F101 code is tailored to minimise the effect of uncertainties due to defect sizing. The authors have added prediction capabilities to the capacity equation by introducing a standard deviation model of future predicted defect depth. By doing so, the variation of safety factors of the capacity equation has been manipulated to that extend where prediction of future pipeline remaining life-time becomes feasible. The paper demonstrates derivation of time-function standard deviation equation, *Std(d/t)* of tool error, calculation and prediction of pipeline remaining lifetime subject to internal corrosion. The increment of standard deviation of corrosion depth, *Std(d/t)* was addressed since it can affect the value of partial safety factor as corrosion progresses, hence amplifying the conservatism of time to failure. The prediction results shows that the dynamic of safety factors has successfully downgraded the structure resistance as corrosion progresses to reflect the actual condition of the pipeline on site. The technique to evaluate future pipeline remaining lifetime can effectively assist pipeline operators to evaluate future safe operating strategies including re-inspection and appropriate maintenance schedule. As a result, it can minimise the likelihood of pipeline failures until it reaches its designed lifetime.

KEYWORDS: *Pipeline, DNV RP-F101, corrosion, reliability, deterministic*

## Introduction

Transporting crude oil and gas by the means of pipelines systems has become the safest and most economical method in the world as compared to tankers, provided that the long-term integrity of the line is well-secured. Unfortunately, the increasing number of aging pipelines in operation has significantly increased the number of accidents [Teixera *et al*., 2008]. As a pipeline ages, it can be affected by a range of corrosion mechanisms, which may lead to a reduction in its structural integrity and eventual failure [Ahammed, 1997; Netto *et al*, 2005; Teixera *et al*., 2008]. Corrosion is an important form of pipeline deterioration due to aggressive environments [Ahammed and Melchers, 1996&1997]. Without a practical and effectual corrosion-prevention strategy, corrosion will continue to progress and the cost of repairing

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a deteriorating pipeline will escalate. Significant savings are possible by optimising the inspection and corrosion-prevention strategies [Ainouche, 2006].

**Pipeline Inspection**

In line inspection (ILI) tools, also commonly called pipeline inspection gauge or 'pig', are devices used by the pipeline industry to survey mainly the internal condition of the pipeline wall. Intelligent Pig, a tool with the capability of mapping anomalies, is widely deployed to detect, locate and measure the size of a corrosion defect in a pipeline using high-resolution Magnetic Flux Leakage (MFL) or Ultrasonic Testing (UT) techniques. The past 40 years has seen the development of a number of methods for assessing the significance of defects. Some of these have been incorporated into industry guidance [Cosham *et al*., 2007]. The nucleation of defects in the pipeline can result in a serious wall thinning in a pipeline. Whereas MFL provides a versatile and reliable method for determining the geometry of metal loss in pipelines, UT allows direct and fairly accurate measurements of pipeline wall thickness. However, the UT tool is limited in terms of usability on gas pipeline since the tool requires medium to transmit and receive back the ultrasonic signal during ILI inspection.

**Research Problem and Methodology**

The inherent uncertainties embedded within metal-loss data play significant roles in reducing the accuracy of pipeline future assessment. These uncertainties are related to imperfect tool measurement, uncontrolled environment and variation of operational data [Yahaya *et. al*, 2011]. Furthermore, the complexity of corrosion mechanism involving numerous unknown factors and limited resolution by the inspection tool can jeopardize the integrity of structure assessment practice [Din *et. al*, 2009]. To cater to the uncertainties, the DNV RP-F101 [DNV, 2004] has incorporated safety factors into the capacity equation which are specially tailored to account for uncertainties associated with defect depth. Unlike conventional safety factors, the value is dependent upon inspection tool accuracy which is defined by the dispersion of corrosion growth-rate value and metal-loss data. The authors have manipulated the polynomial equation of safety factors in the DNV RP-F101 to make the capacity equation capable of predicting the future growth of defects. This is done by deriving a time-function standard deviation equation, *Std(d/t)* of the inspection tool. The predicted metal-loss data in the future is supposed to pose higher variation from its central tendency value compared to actual metal-loss data. Hence, a higher safety factor to cater for defect depth is necessary to increase the conservatism of assessment as well as to have a more realistic assessment due to rapid reduction of structure capacity.

***Metal Loss Information***

In this case study, an extensive amount of pigging data has been gathered through repeated in-line inspection activities using MFL intelligent pig on the same pipelines at different points of time. The transmission pipelines located in the North Sea region used to convey crude oil and gas (multiphase line) from central offshore platform to onshore terminal. The data provides valuable information on the internal corrosion defect geometry, such as defect location, depth and length, orientation and types of corrosion regions. The data were used to evaluate the current state of the pipe under corrosion attack using the DNV RP-F101 equation. The authors have incorporated a statistical concept into the pipeline evaluation procedure so that future prediction of pipeline remaining capacity can becomes feasible. A new equation of standard deviation, *Std [d/t]* reflects the defect sizing by the inspection tool has been derived from linear metal-loss rate equation based on the statistical principle. This equation is meant to recalculate the new safety factor and fractile value for future state whereby the factors are required by the DNV RP-F101 capacity equation to estimate the remaining life of a corroding pipeline.

### *Assessment of Corroding Pipeline*

Theoretically, the safety factors introduced to represent uncertainties associated with load system and structure resistance (material strength) is commonly found in all codes of assessment for corroded pipelines. Nonetheless, the safety factor has led to a certain level of degree of conservatism in regard to structural assessment causing over prediction of deterioration intensity [Ozman *et. al*, 2010]. The uncertainties subjected to structural properties, loading condition, environmental behaviour and construction performance are always neglected in the calculation due to the employment of a safety factor. In pipeline assessment, deterministic assessment is a straight-forward approach based on codes or developed capacity equation. Generally, the deterministic methods use lower bound data; for instance, peak depth of corrosion, maximum corrosion rate and minimum wall thickness without considering the existing uncertainties [Yahaya, 2000]. Consequently, it can be over conservative in terms of safety when being implemented to pipelines containing extensive corrosion defects. For example, the prediction of future growth of corrosion defects located in the pipelines normally is based on averaged single rate value without considering the possibility that not all defects will grow at the same rate. The averaged rate is used for the sake of simplicity owing to lack of information pertaining to environmental and material properties [Noor *et. al*, 2008].

Assessment method is required to determine the severity of such defects when they are detected in pipelines [Cosham and Hopkins, 2003]. The assessment of the condition of existing oil and gas pipelines is necessary in order to protect the public, financial investment and environment from such failures. Systematic and optimised regular inspections of pipelines with state-of-the art tools and procedures can reduce significantly the risk of any undue accident caused by a lack of unawareness of the integrity of the line [Cosham *et al*., 2007].

### *DNV Recommended Practice (RP-F101)Criteria*

The DNV Recommended Practice for the assessment of corroded pipelines was first issued in 1999. RP-F101 describes two alternative approaches with different safety philosophies. The equations in the DNV RP-F101 were derived by a probabilistic calibration taking into account the uncertainties in defect measurements and burst capacity [Bjornoy and Marley, 2001]. The equations account directly for the accuracy in sizing the corrosion defect. The DNV RP –F101 recommends the assessment of corroded pipelines subject to internal pressure and internal pressure combined with longitudinal compressive stresses [Bjornoy and Marley, 2001]. Moreover, this new criterion also provides an assessment procedure for single defect, interacting defects and complex shaped defects.

*Capacity Equation*

The capacity equation is a mathematical model used to estimate the remaining pressure capacity of the line after the initiation of corrosion defect. The maximum allowed operating pressure in pipelines for a single defect presented by the DNV RP-F101 [DNV, 2004] is given as:

$$P_p = \frac{\gamma_m \times 2 \times t \times SMTS \times (1-\gamma_d (d/t)^*)}{(D-t)(1-\gamma_d (d/t)^* Q^{-1}} \leq P_{mao} \quad (1)$$

where;

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

$$(d/t)^* = (d/t)_{meas} + \varepsilon_d StD[d/t] \quad (3)$$

and;

$D$ = outer diameter (*mm*)
$d$ = depth of corrosion defect (*mm*)
$t$ = nominal pipe wall thickness (*mm*)
$L$ = measured length of corrosion defect (*mm*)
$d/t$ = ratio of corrosion depth to pipe wall thickness
$(d/t)_{meas}$ = measured relative corrosion depth
$(d/t)^*$ = actual relative corrosion depth to cover uncertainties related to inspection tool

$g_m$ = partial safety factor for prediction model and safety class
$g_d$ = partial safety factor for corrosion depth
$e_d$ = factor for defining a fractile value for the corrosion depth
$P_{mao}$ = maximum allowable operating pressure (*MPa*)
*StD[d/t]*= standard deviation for measurement (*d/t*) ratio
*SMTS* = specified minimum tensile strength (*N/mm*$^2$)

Fundamentally, equation (1) is similar to ASME B31G [B31G, 1991]. However, the difference between these two criteria is that partial safety factors are included in the DNV RP-F101 equation to ensure a consistent reliability level for various combinations of material properties, pipe geometries and corrosion defects configurations.

*Partial Safety Factors*

The concept of partial safety factors is different from sole safety factors in that both strength and load system have to be multiplied with multiple safety factors. In pipeline assessment, the partial safety factors $g_m$ and $g_d$, and the fractile value $e_d$ are determined from tables which depend on the safety class classification, the pipe quality, inspection method and sizing accuracy of the inspection tool [DNV, 2004]. They were given as functions of the sizing accuracy of the measured defect depth for inspections based on relative depth measurements and for inspections based on absolute depth. The safety class is specified based on Tables 1 to 3.

Table 1. Partial safety factor $g_m$, [DNV, 2004].

| Inspection Method | Safety class | | |
|---|---|---|---|
| | Low | Normal | High |
| Relative (e.g. MFL) | $\gamma_m = 0.79$ | $\gamma_m = 0.74$ | $\gamma_m = 0.70$ |
| Absolute (e.g. UT) | $\gamma_m = 0.82$ | $\gamma_m = 0.77$ | $\gamma_m = 0.72$ |

Table 2. Standard deviation, *StD [d/t]*, for MFL inspection tool [DNV, 2004].

| Relative sizing accuracy | Confidence level | |
|---|---|---|
| | 80% | 90% |
| Exact ± (0.0 of t) | StD[d/t] = 0.00 | StD[d/t] = 0.00 |
| ± 0.05 of t | StD[d/t] = 0.04 | StD[d/t] = 0.03 |
| ± 0.10 of t | StD[d/t] = 0.08 | StD[d/t] = 0.06 |
| ± 0.20 of t | StD[d/t] = 0.16 | StD[d/t] = 0.12 |

Table 3. Partial safety factor, $g_d$ and fractile value factor, $e_d$ [DNV, 2004].

| Inspection sizing accuracy StD[d/t] | $\varepsilon_d$ | Safety class Low | Normal | High |
|---|---|---|---|---|
| (exact) 0.00 | 0.0 | $\gamma_d = 1.00$ | $\gamma_d = 1.00$ | $\gamma_d = 1.00$ |
| 0.04 | 0.0 | $\gamma_d = 1.16$ | $\gamma_d = 1.16$ | $\gamma_d = 1.16$ |
| 0.08 | 1.0 | $\gamma_d = 1.20$ | $\gamma_d = 1.28$ | $\gamma_d = 1.32$ |
| 0.16 | 2.0 | $\gamma_d = 1.20$ | $\gamma_d = 1.38$ | $\gamma_d = 1.58$ |

**Pipeline Remaining Lifetime**

The steel pipeline has a 14.2 mm wall thickness with outside diameter given as 914.4 mm. The allowable defect size of the pipeline is indicated by the uppermost curve, i.e. the acceptance line (refer to Figures 1 to 5). Once the corrosion point exceeds the acceptance line, the pipeline is considered to be in a critical condition. Hence, inspection and repair are recommended to commence. The mean value and standard deviation of the corrosion rate used in this assessment are 0.0405 mm/year and 0.08 mm/year respectively. The acceptance line was constructed using equation (1). From this equation, the maximum corrosion defect length was estimated by fixing the ratio of corrosion depth in percentage, *d/t* between 10*% wt* to 100*%wt (wt = pipe wall thickness)* and with the different working pressures of 8MPa, 9MPa and 10MPa. By taking out the defect length parameter, an equation of length correction factor, *Q* can be written as:

$$Q = \frac{\gamma_d \left(\frac{d}{t}\right)^*}{\left[1 - \frac{\gamma_m 2tSMTS\left(1 - \gamma_d \left(\frac{d}{t}\right)^*\right)}{(D-t)P_p}\right]} \tag{4}$$

Since *Q* can also be represented by equation (2), the maximum allowable defect length for a given defect depth and working pressure can be calculated as:

$$L_{max} = \sqrt{\frac{(Q^2 - 1)}{0.31}} \times \sqrt{Dt} \tag{5}$$

where:

$L_{max}$ = maximum allowable defect length (mm)

The *Q* expression in equation ( 5) can be calculated by inserting Equation 4 into Equation 5 so the allowable line/ acceptance line to evaluate pipeline condition can be constructed. The increment value of *Std [d/t],* $g_d$ and $e_d$ in the future can be estimated using Table 4 as given in the DNV RP-F101 code.

The augmentation of prediction capabilities of equation (1) by increasing the standard deviation of *d/t* can be explained mathematically by referring to the linear growth rate model. The corrosion rate equation can be written as:

$$CR = \frac{d_{t_{i+1}} - d_{t_i}}{T} \tag{6}$$

where $T = t_{i+1} - t_i$ and is a constant value.

If corrosion depth *d* is assumed statistically varied, the variation of corrosion rate can be expressed as:

$$\text{variance}(CR) = \text{variance}\left(\frac{d_{t_{i+1}} - d_{t_i}}{T}\right) \tag{7}$$

Since the time interval, *T* is a single value with no variation, Equation 7 can be rewritten as:

$$\sigma_{CR}^2 = \frac{1}{T^2}.\text{variance}(d_{t_{i+1}} - d_{t_i}) \tag{8}$$

and simplified into:

$$\sigma_{CR}^2 = \frac{1}{T^2}\left(\sigma[d]^2_{t_{i+1}} - [d]\sigma^2_{t_i}\right) \tag{9}$$

Therefore, the relationship between inspection time interval and the variation in corrosion growth rate can be presented as:

$$\sigma_{CR} = \frac{1}{T}\sqrt{\left(\sigma[d]^2_{t_{i+1}} - \sigma[d]^2_{t_i}\right)} \tag{10}$$

Since s=*Std*, therefore

$$Std_{CR} = \frac{1}{T}\sqrt{\left(Std[d]^2_{t_{i+1}} - Std[d]^2_{t_i}\right)} \tag{11}$$

Inspection data of metal loss from MFL pig tools usually is represented as a ratio of defect depth to wall thickness, *d/t*. By replacing the exact metal-loss value, *d* with metal-loss ratio, *d/t* equation (11) can be rewritten as follows;

$$Std\left[\frac{cr}{t}\right] = \frac{1}{T}\sqrt{\left(Std\left[\frac{d}{t}\right]^2_{t_{i+1}} - Std\left[\frac{d}{t}\right]^2_{t_i}\right)} \tag{12}$$

Equation (12) now can be reshuffled to make it as a standard deviation model of predicted depth. The new form of equation as a function of variation of defect from previous inspection,

inspection time interval and variation of corrosion rate is as follows;

$$T.Std\left[\frac{cr}{t}\right] = \sqrt{\left(Std\left[\frac{d}{t}\right]^2_{t_{i+1}} - Std\left[\frac{d}{t}\right]^2_{t_i}\right)} \quad (13)$$

$$Std\left[\frac{d}{t}\right]_{t_{i+1}} = \sqrt{Std\left[\frac{d}{t}\right]^2_{t_i} + T^2.Std\left[\frac{cr}{t}\right]^2} \quad (14)$$

By assuming the wall thickness, $t$ as a fixed value with no variation, the conclusive equation can be presented as

$$Std[d/t]_T = \sqrt{Std([d/t]_o)^2 + \frac{T^2}{t^2}Std[cr]^2} \quad (15)$$

where:

cr = corrosion rate *(mm/year)*

$Std[d/t]_o$ = Standard deviation of inspection tool in first year assessment.

$Std[d/t]_T$ = Standard deviation of inspection tool in the future.

Std[cr] = Standard deviation of corrosion rate.

T = prediction interval in year

$t_i$ = year of inspection

$\sigma^2_{cr}$ = variance of corrosion rate *(mm/year)*$^2$

The equation depicts relationship between deviation of predicted data and the interval of prediction. The longer the prediction interval, the higher the variation of future metal loss, hence the higher the partial safety factors for metal loss. Table 4 shows the equations required to estimate the partial safety factors for metal loss and fractile value according to the range of metal loss standard deviation, *Std[d/t]*.

**Results and Discussion**

Pipeline time to failure was determined using the DNV RP-F101 capacity equation (*Part A*) [DNV, 2004]. Figures 1 to 5 show the prediction result of pipeline assessment subject to internal corrosion from year $t_0$ to $t_{10}$. These predictions were based on gathered corrosion data from pigging inspection done in year $t_0$. From the assessment result in year $t_0$ and $t_2$, the measured corrosion defect is within the acceptance criteria for all operating pressures where there are no defects exceeding the acceptance line as shown in Figures 1 and 2. Further prediction was made from year $t_5$ until $t_{10}$. As can be seen in Figures 3 to 5, the corrosion depth begins to exceed the acceptance line starting from year $t_5$ when the pipeline is operated under 9MPa and 10MPa of operating pressure. The pipeline is considered critical condition due to bursting in year $t_5$ when the acceptance criteria for all operating pressures were exceeded by the projected defects. Based on the result, it can be concluded that the pipeline should be inspected no later than year $t_5$ for every condition of operating pressure. The acceptance line predicted by the corrosion defect in year $t_5$ until $t_{10}$ was found to be lower than the one estimated for the $t_0$ and $t_2$ predictions. This is hypothecally owing to the increment of uncertainties related to the averaged corrosion growth rate [Noor *et. al*, 2007]. Figures 6 to 8 show the increment of *StD[d/t],* fractile value, $e_d$ and safety factor, $g_d$ over the year, $t_n$. The increment of *StD[d/t]* over time exhibits the exponential shape indicating the growth of uncertainties along with the projection of future

Table 4. Polynomial equation for partial safety factor (defect depth) and fractile value [DNV, 2004].

| Safety Factors | $\gamma_d$ and $\varepsilon_d$ | Range |
|---|---|---|
| Low | $\gamma_d = 1.0 + 4.0\ StD[d/t]$ | $StD[d/t] < 0.04$ |
| | $\gamma_d = 1 + 5.5\ StD[d/t] - 37.5\ StD[d/t]^2$ | $0.04 \le StD[d/t] < 0.08$ |
| | $\gamma_d = 1.2$ | $0.08 \le StD[d/t] \le 0.16$ |
| Normal | $\gamma_d = 1 + 4.6\ StD[d/t] - 13.9\ StD[d/t]^2$ | $StD[d/t] \le 0.16$ |
| High | $\gamma_d = 1 + 4.3\ StD[d/t] - 4.1\ StD[d/t]^2$ | $StD[d/t] \le 0.16$ |
| (all) | $\varepsilon_d = 0$ | $StD[d/t] \le 0.04$ |
| | $\varepsilon_d = -1.33 + 37.5\ StD[d/t] - 104.2\ StD[d/t]^2$ | $0.04 \le StD[d/t] \le 0.16$ |

defect growth . Fractile value, $e_d$ and safety factor, $g_d$ follow the polynomial law and become constant when projection exceeded period of 10 years. This gives an indication that the projection reliability is not meant for long-term prediction of pipeline future state due to extreme unforeseen events. Equation (15) and Table 4 were used to recalculate the abovementioned values as corrosion progresses in time.

## Conclusion

The great advantages of the deterministic approach are due to its simplicity and the capability of being applied to an entire pipeline or collection of pipelines straightforwardly [Lawson, 2005]. The inability to deal with uncertainties in the input data is the primary weakness of deterministic approach which leads to inaccurate interpretation of pipeline condition

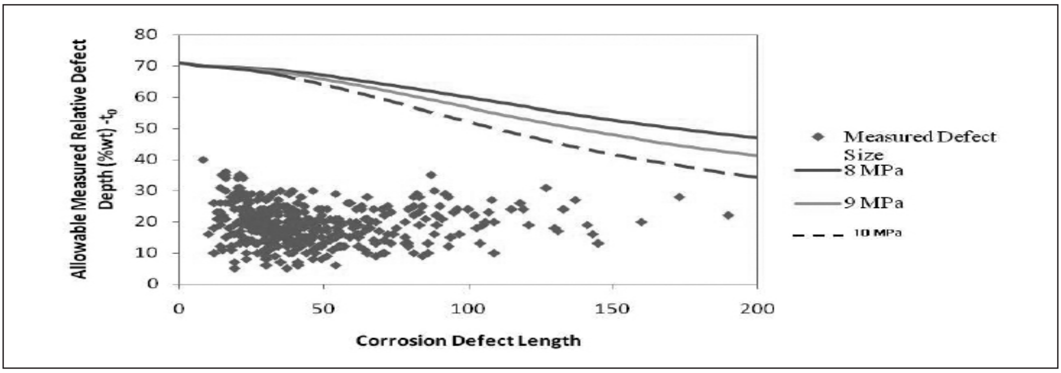


Figure 1. Projection of corrosion depth in year $t_0$.

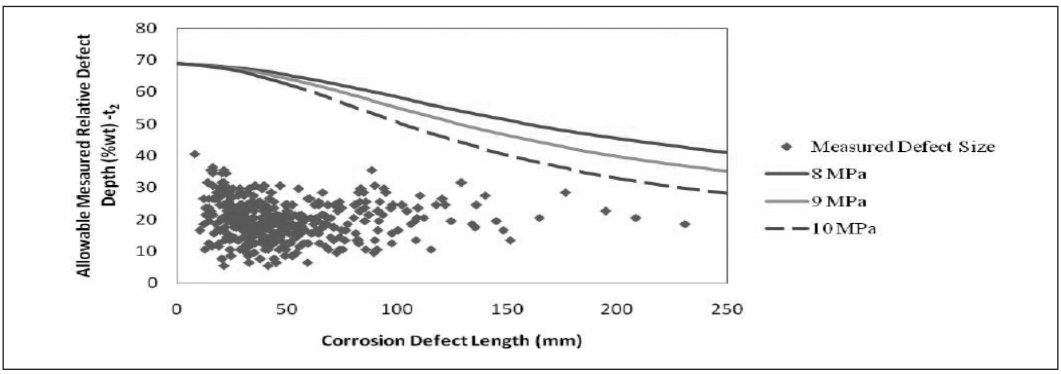


Figure 2. Projection of corrosion depth in year $t_2$.

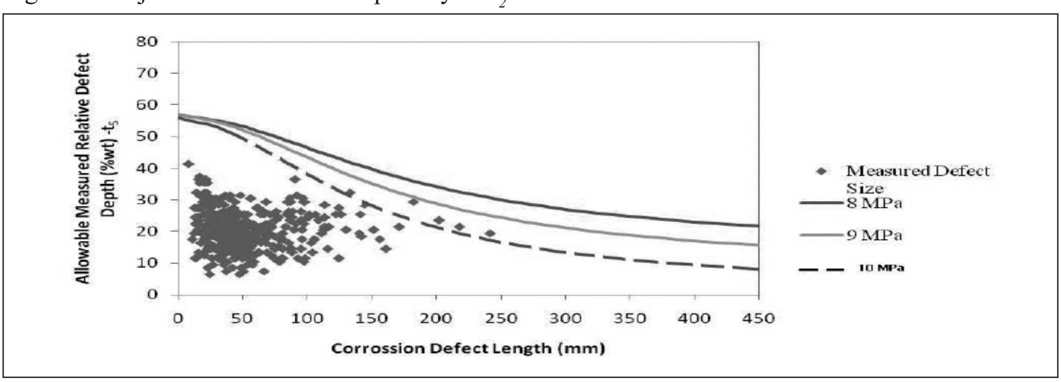


Figure 3. Projection of corrosion depth in year $t_5$.

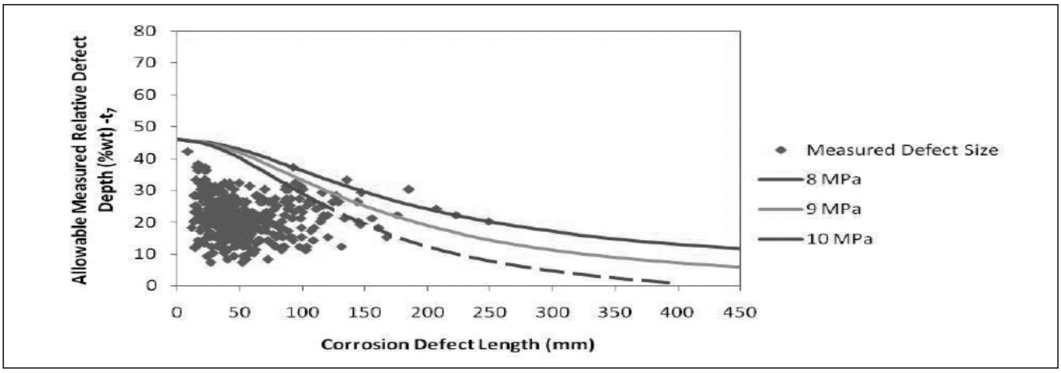


Figure 4. Projection of corrosion depth in year $t_7$ using DNV RP-F101 Assessment code.

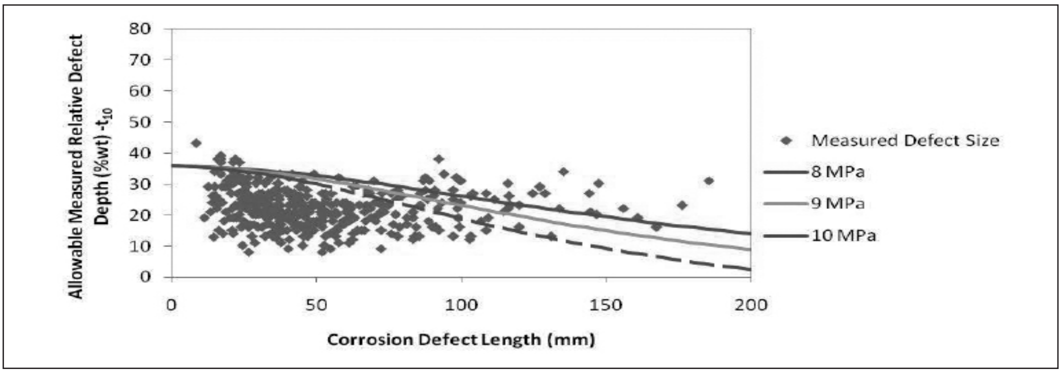


Figure 5. Projection of corrosion depth in year $t_{10}$ using DNV RP-F101 Assessment code.

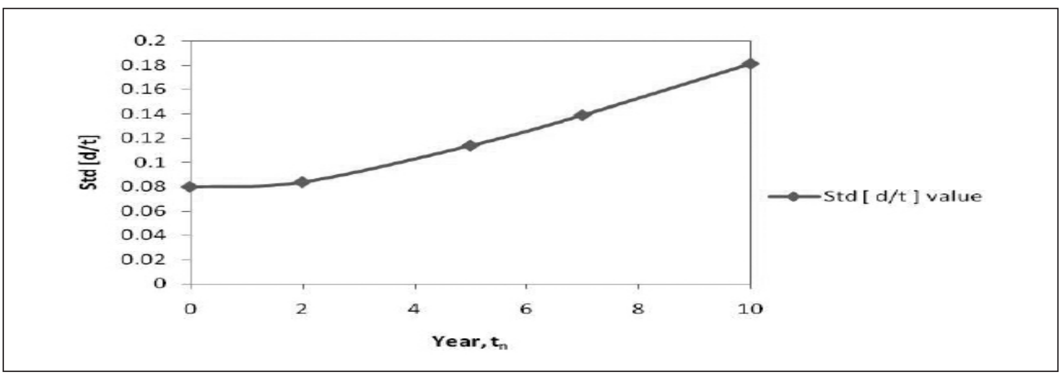


Figure 6. The increment of *StD[d/t]* over time.

and not entirely due to error of inspection data [Lawson, 2005]. Therefore, a prediction of pipeline integrity by using a deterministic assessment methodology cannot effectively fulfill the cost-saving requirement by the operators. A semi-probabilistic theory was introduced in the DNV RP-F101 code by estimating the standard deviation of inspection tool error and defect sizing. This is a result of the requirement that the operators have to inspect their pipelines frequently in order to obtain better information on pipeline condition. The introduction of partial safety factors to minimise the effect of uncertainties due to the defect sizing and standard deviation model of future metal loss has improved the capability of predicting the future growth of corrosion defects

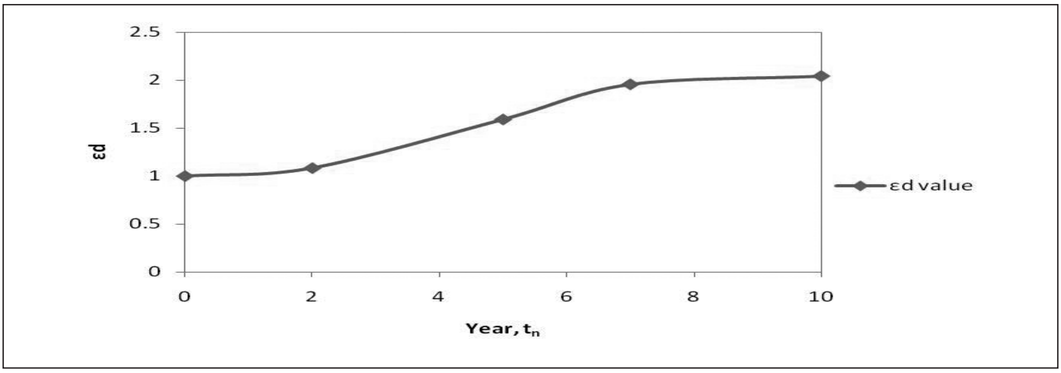


Figure 7. The increment of fractile value, $e_d$ over time.

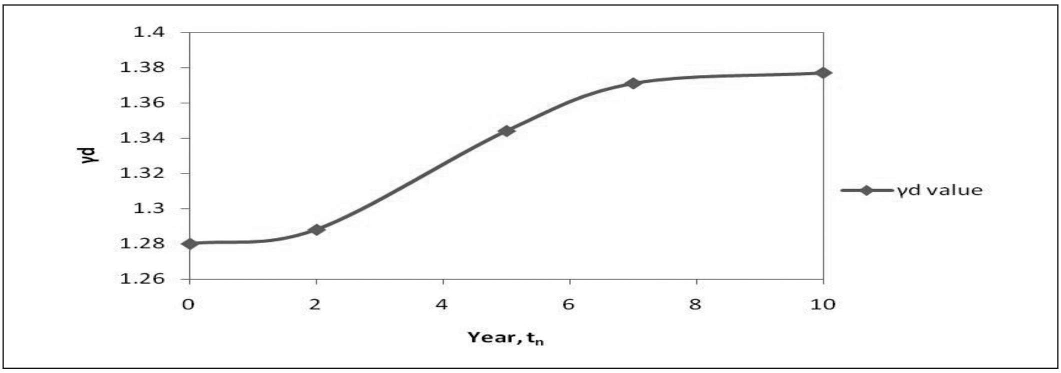


Figure 8: The increment of safety factor, $g_d$ over time.

deterministically. In addition, a new equation was derived so that the partial safety factors can be recalculated so as to take into account the growth of uncertainties as corrosion progresses. This technique ensures that the resistance system will be naturally downgraded as the load system approaches the limit state due to corrosion to reflect the actual load-resistance interference law.

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