Effect of Boundary Conditions of Failure Pressure Models on Reliability Estimation of Buried Pipelines

Ouk-Sub Lee[1,#], Jang-Sik Pyun[1] and Dong-Hyeok Kim[1]

[1] School of mechanical engineering, InHa University, Incheon, South Korea

ABSTRACT

This paper presents the effect of boundary conditions in various failure pressure models published for the estimation of failure pressure. Furthermore, this approach is extended to the failure prediction with the aid of a failure probability model. The first order Taylor series expansion of the limit state function is used in order to estimate the probability of failure associated with each corrosion defect in buried pipelines for long exposure period with unit of years. A failure probability model based on the von-Mises failure criterion is adapted. The log-normal and standard normal probability functions for varying random variables are adapted. The effects of random variables such as defect depth, pipe diameter, defect length, fluid pressure, corrosion rate, material yield stress, material ultimate tensile strength and pipe thickness on the failure probability of the buried pipelines are systematically investigated for the corrosion pipeline by using an adapted failure probability model and varying failure pressure model.

Key Words : Rackwitz-Fiessler Transformation Method, Log-Normal Distribution, Normal Distribution, Buried Pipeline, Corrosion, Failure Probability, Reliability Estimation, Failure Pressure Model

1. Introduction

The skill of maintenance and management of the industrial equipments has been emerged as a very important technique to be properly dealt with because the industrial apparatus becomes more complicated and diversified throughout all kinds of industries with the development of various mechanical techniques. It has been often reported as an industrial example that a catastrophic disaster has been caused by the defect such as corrosion arisen by aging and/or environmental effects on pipeline transporting gas and oil(1,2).

The technique to predict pipeline failure due to corrosion damage is necessary to determine the corrosion tolerance when we design pipelines. Especially, it may be inevitable technical information to assess the safety life of aging pipelines. Therefore, systematic investigations which study the damage and the failure of pipelines corresponding to varying boundary conditions are needed.

It is generally well known that the occurrence of corrosion in pipelines reduces the strength of pipeline material. Thus, the development of reference and/or standard is required to prevent failure accidents in advance by predicting the stress condition and failure life corresponding to the shape and location of corrosion(3-7).

The buried pipelines have the various types of defects such as corrosion and environment-assist-cracking. If these were operated under an excessive operating pressure in the corroded pipelines, it could produce larger stresses than designed one. Because it may lead to uncertainty in the failure analysis with varying boundary conditions, the failure analysis should be carried out with the help of probability method than the deterministic approach (8,9).

In this paper, various strength assessment methods were compared and analyzed for the defect region of

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Corresponding Author:
Email: leeos@inha.ac.kr
Tel: +82-32-860-7315, Fax: +82-32-868-1716

pipeline with internal operating pressure. For each model, using the FORM(first-order reliability method) which is one of the probability analysis method with reliability index, the effects of various boundary conditions on the failure probability of pipeline are systemically investigated.

2. Failure Probability

2.1 First-order reliability method

The failure probability is calculated using FORM which is one of the methods utilizing reliability index [8,9].

The FORM method derives its name from the fact that it is based on a first-order Taylor series approximation of the performance function or limit state function and uses only second-moment statistics (means and variances) of the random variables. A limit state function is defined as

$$Z = R - L \tag{1}$$

where R is the resistance normal variable, and L is the load normal variable. Assuming that R and L are statistically independent normally distributed random variables, the variable Z is also normally distributed. Its mean and variance can be determined readily as

$$\mu_Z = \mu_R - \mu_L \tag{2}$$

$$\sigma_Z^2 = \sigma_R^2 + \sigma_L^2 \tag{3}$$

where μ_Z, μ_R and μ_L are the means of variables Z, R and L, respectively and σ_Z^2, σ_R^2 and σ_L^2 are the variances of variables Z, R and L respectively.

The event of failure occurs when R<L, and Z<0. The probability of failure(PF) is given by

$$PF = P[Z < 0]$$

$$= \int_{-\infty}^{0} \frac{1}{\sigma_Z\sqrt{2\pi}} \exp\left\{-\frac{1}{2}\left(\frac{Z-\mu_Z}{\sigma_Z}\right)^2\right\} dZ \tag{4}$$

where new variable U is $U = (Z - \mu_Z)/\sigma_Z$. The PF of Eq. (4) is given by

$$PF = \int_{-\infty}^{-\beta} \frac{1}{\sqrt{2\pi}} \exp\left\{-\frac{u^2}{2}\right\} du$$

$$= P[Z < 0] = \Phi(-\beta) \tag{5}$$

where Φ is cumulative distribution function for a standard normal variable. Thus, the probability of failure depends on the ratio of the mean value of Z to its standard deviation. This ratio is commonly known as the safety index or reliability index and is denoted as β:

$$\beta = \frac{\mu_Z}{\sigma_Z} = \frac{\mu_R - \mu_L}{\sqrt{\sigma_R^2 + \sigma_L^2}} \tag{6}$$

2.2 Rackwitz-Fiessler transformation method

Rackwitz and Fiessler[10] estimated the parameters of the equivalent normal distribution, μ_X^N and σ_X^N, by imposing two conditions. The cumulative distribution functions and the probability density functions of the actual variables and the equivalent normal variables should be equal at the checking point(x^*) on the failure surface. Considering each statistically independent non-normal variable individually and equating its cumulative distribution function with an equivalent normal variable at the checking point result in

$$F_X(x^*) = \Phi\left(\frac{x^* - \mu_X^N}{\sigma_X^N}\right) \tag{7}$$

$$\mu_X^N = x^* - \Phi^{-1}\left(F_X(x^*)\right)\sigma_X^N \tag{8}$$

where Φ is the cumulative distribution function of the standard normal variable, μ_X^N and σ_X^N are the mean and standard deviations of the equivalent normal variable at the checking point, respectively.

Equating probability density functions of the original variable and equivalent normal variable at the checking point result in

$$f_X(x^*) = \frac{1}{\sigma_X^N}\phi\left(\frac{x^* - \mu_X^N}{\sigma_X^N}\right) \tag{9}$$

$$\sigma_X^N = \frac{\phi\left[\Phi^{-1}\left(F_X(x^*)\right)\right]}{f_X(x^*)} \tag{10}$$

where ϕ is the probability density function of the standard normal variable.

The non-normal variables can be treated as normal distributed variables through the transformation of Eqs.(8) and (10).

3. Failure Pressure Models

The major causes of the failure of pipelines transporting the high pressure gas are known to be mechanical damage and corrosion.

Standards for a regular hydrostatic test and a corrosion assessment are generally used to assess the effect of the mechanical damage and corrosion on the integrity of the pipelines. To assess the integrity of corrosion pipeline, we need to simplify the geometry of the vicinity of corrosive part.

Fig. 1 shows a corrosion model and is generally further simplified as shown in Fig. 2 to analyze the given geometric configuration easily.

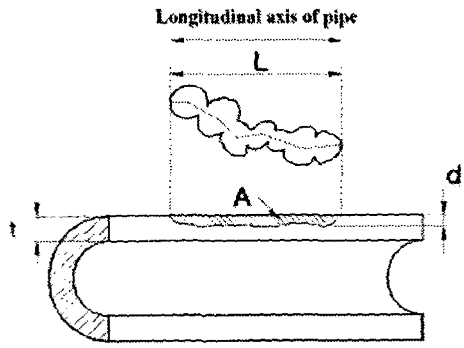


Fig. 1 A simplification of a corroded surface flaw in a pipeline

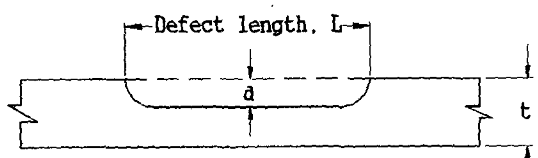


Fig. 2 Section through an idealized corrosion defect

3.1 ANSI/ASME B31G code

The modified failure formula for a parabola and a rectangular shape are given, respectively, as follows [8]:

3.1.1. Parabola

$$P_f = 1.11\frac{2\sigma_{min}t}{D}\left[\frac{1-(2/3)(d/t)}{1-(2/3)(d/t)/M}\right]$$

$$\left(\text{for} \quad \sqrt{0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)} \le 4\right) \qquad (11)$$

where P_f is the failure pressure, D is the outer diameter of pipe and σ_{min} is the lower yield strength.

3.1.2. Rectangular

$$P_f = 1.1\frac{2\sigma_{min}t}{D}\left[1-(d/t)\right]$$

$$\left(\text{for} \quad \sqrt{0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)} > 4\right) \qquad (12)$$

The bulging factor is defined as

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

$$\left(\text{for} \quad \sqrt{0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)} \le 4\right) \qquad (13)$$

$$M = \infty$$

$$\left(\text{for} \quad \sqrt{0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)} > 4\right) \qquad (14)$$

3.2. MB31G(Modified B31G) code

Kiefner et al pointed out some problems on the definition of flow stress $(\bar{\sigma} = 1.1\sigma_{min})$ and bulging factor, and proposed a new flow stress such as $\bar{\sigma} = 1.1\sigma_{min} + 69$ (MPa) and a new bulging factor as follows [8]:

$$P_f = \frac{2(\sigma_{min}+69)t}{D}\left[\frac{1-0.85d/t}{1-0.85(d/t)/M}\right] \qquad (15)$$

$$M=\sqrt{1+0.63\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)-0.0034\left(\frac{L}{D}\right)^4\left(\frac{D}{t}\right)^2}$$

$$\left(\text{for}\quad\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)\le 50\right) \tag{16}$$

$$M=3.3+0.032\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)$$

$$\left(\text{for}\quad\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)> 50\right) \tag{17}$$

3.3. Battelle model

At Battelle, they considered that fracture toughness took an important role in the failure stress of the pipelines with corrosion defects and that high toughness pipelines were broken by plastic collapse[8].

$$P_f=\frac{2\sigma_{uts}t}{D}\left[1-(d/t)/M\right] \tag{18}$$

The bulging factor is defined as

$$M=1-\exp\left(-0.157\frac{L}{\sqrt{D(t-d)/2}}\right) \tag{19}$$

where σ_{uts} is the material ultimate tensile strength.

3.4. Shell-92 model

Ritchie and Last proposed new failure pressure criterion by modifying ASME B31G[8]. The modified criterion included an effect for the material level and simply expressed geometrical shape about size of corroded region.

$$P_f=\frac{1.8\sigma_{uts}t}{D}\left[\frac{1-(d/t)}{1-(d/t)/M}\right] \tag{20}$$

The bulging factor is defined as

$$M=\sqrt{1+0.805\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)} \tag{21}$$

3.5. Chell Limit Load Analysis

This criterion proposed by Chell took possession of R6 which was failure assessment steps of British CEGB(Central Electricity Generation Board) [8].

$$P_f=1.1\frac{2\sigma_{\min}t}{D}\left[1-(d/t)+(d/t)/M\right] \tag{22}$$

The bulging factor is defined as

$$M=\sqrt{1+1.61\left(\frac{\pi}{8}\right)^2\left(\frac{2L^2}{Dd}\right)} \tag{23}$$

where $\sigma_{\min}$ is the material ultimate tensile strength.

4. Calculation Principles

The main assumption of the probabilistic reliability analysis for the corroded pipelines is the randomness of load and resistance parameters determining the limit state functions. It should be necessary to define a failure function when the failure probability analysis is carried out. The failure function may be expressed as a reference for the pipeline failure and must include the failure pressure and the operation service pressure. The operation service pressure is just the pressure of the fluid that flows inside the pipeline. A failure function(Z_f) can be postulated as the difference between the failure pressure(P_f) and the operation service pressure(P_a) [11]. Thus,

$$Z_f=P_f-P_a \tag{24}$$

The limit state function depends on the same parameters that P_f does, including the time dependence of the defect size. The dependence of limit state function on the load and resistance variables is determined by the failure pressure model. A general form of the limit state function defined in expression can be expressed as:

$$Z=P_f(\sigma_{ys}\ or\ \sigma_{uts},D,T,t,d,L,R_d)-P_a \tag{25}$$

where σ_{ys} is the yield stress, σ_{uts} is the material ultimate tensile strength, D is the diameter of pipeline, T

is the elapsed time, t is the thickness of pipeline, d is the depth of corrosion, L is the axial length of the defect and R_d is the corrosion rate.

It is generally accepted to represent the average failure probability as

$$PF = P[Z_f < 0] = \Phi(-\beta) \tag{26}$$

β is the reliability index and can be expressed in terms of the average of $Z(\mu_Z)$ and the standard deviation σ_Z as

$$\beta = \frac{\mu_Z}{\sigma_Z} \tag{27}$$

where

$$\begin{aligned}\mu_Z &= Z(\sigma^*_{ys}\ or\ \sigma^*_{uts}, D^*, T^*, t^*, d^*, L^*, R^*_d, P^*_a)\\ &+\left((\overline{\sigma_{ys}}-\sigma^*_{ys})\frac{\partial Z}{\partial \sigma_{ys}}\ or\ (\overline{\sigma_{uts}}-\sigma^*_{uts})\frac{\partial Z}{\partial \sigma_{uts}}\right)\\ &+(\overline{D}-D^*)\frac{\partial Z}{\partial D}+(\overline{T}-T^*)\frac{\partial Z}{\partial T}+(\overline{t}-t^*)\frac{\partial Z}{\partial t}\\ &+(\overline{d}-d^*)\frac{\partial Z}{\partial d}+(\overline{L}-L^*)\frac{\partial Z}{\partial L}+(\overline{R_d}-R^*_d)\frac{\partial Z}{\partial R_d}\\ &+(\overline{P_a}-P^*_a)\frac{\partial Z}{\partial P_a}\end{aligned} \tag{28}$$

$$\begin{aligned}\sigma_Z^2 &= \left((\sigma_{\sigma_{ys}}\frac{\partial Z}{\partial \sigma_{ys}})^2\ or\ (\sigma_{\sigma_{uts}}\frac{\partial Z}{\partial \sigma_{uts}})^2\right)\\ &+(\sigma_D\frac{\partial Z}{\partial D})^2+(\sigma_T\frac{\partial Z}{\partial T})^2+(\sigma_t\frac{\partial Z}{\partial t})^2+(\sigma_d\frac{\partial Z}{\partial d})^2\\ &+(\sigma_L\frac{\partial Z}{\partial L})^2+(\sigma_{R_d}\frac{\partial Z}{\partial R_d})^2+(\sigma_{P_a}\frac{\partial Z}{\partial P_a})^2\end{aligned} \tag{29}$$

$\overline{\sigma_{ys}}(or\ \overline{\sigma_{uts}}), \overline{D}, \overline{T}, \overline{t}, \overline{d}, \overline{L}, \overline{R_d}$ and $\overline{P_a}$ the average values and $\sigma^*_{ys}(or\ \sigma^*_{uts}), D^*, T^*, t^*, d^*, L^*, R^*_d$ and P^*_a are the values at an inspection time.

$\sigma_{\sigma_{ys}}(or\ \sigma_{\sigma_{uts}}), \sigma_D, \sigma_T, \sigma_t, \sigma_d, \sigma_L, \sigma_{R_d}$ and σ_{P_a} are the average deviation for each variable such as $\sigma_{ys}(or\ \sigma_{uts}),\ D, T, t, d, L, R_d$ and P_a.

Although the standard deviation value is expressed as the same units as the mean value, its absolute value does not clearly indicate the degree of dispersion in the random variable, without referring to the mean value. Since the mean and the standard deviation values are expressed in the same units, a non-dimensional term can be introduced by taking the ratio of the standard deviation and the mean. This is called the coefficient of variation (COV) and will be denoted as COV(X)[8,9]. Thus,

$$COV(X) = \frac{\sigma_X}{\mu_X} \tag{30}$$

5. Example

The variables, the means and the coefficient of the variation listed in Table 1 have been utilized to investigate the effect of each variable on the failure probability of the corrosion pipeline. The applied forces at boundaries except inner pressure of the pipeline are assumed to be negligible [11].

Table 1 Random variables and their parameters used in the example

Variable	Mean	PDF type	COV
D	3 mm	Normal	0.1
D	750 mm	Normal	0.02
L	50 mm	Normal	0.1
P_a	8 MPa	Normal	0.11
σ_{ys}	358 MPa	Log-Normal	0.07
σ_{uts}	455 MPa	Log-Normal	0.067
T	15 mm	Log-Normal	0.02
R_d	0.1 mm/year	Log-Normal	0.1

6. Results and Discussion

Fig. 3 shows the results of the FORM algorithm to compute the total pipeline failure probability using the failure pressure models given in section 3. It is noted from Fig. 3 that the failure probability increases slowly during a period between 15 and 20 years except for Shell-92 model and the increasing rate of the failure probability becomes very steep after 20 years of the exposure period. Furthermore, it is noted that a certain size of corrosion does not affect the failure probability within a certain exposed period of time and a rapid increase of the failure probability occurs after a certain exposed period is elapsed.

The results in Fig. 3 show that the failure pressure models used to predict P_f give similar pipeline failure probabilities for relatively short exposure period (less than 15 years). For long exposure periods, the Shell-92 model gives the highest probabilities of failure while the B31G gives the lowest.

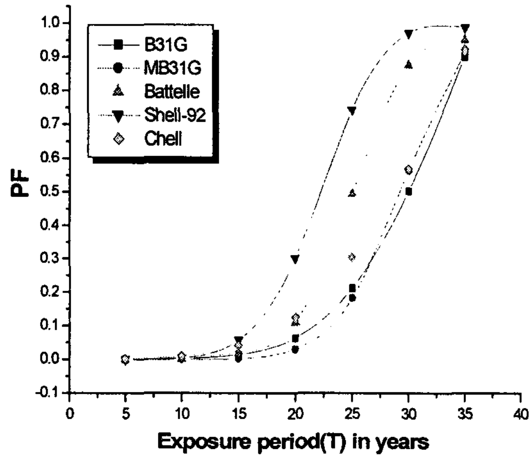


Fig. 3 A relationship between failure probability(PF) and exposure period(T) for several failure pressure models

Fig. 4 shows the relationship between the failure probability of normalized defect length of the corrosion pipeline and the exposed period in year. The results in Fig. 4 show similar pipeline failure probabilities for relatively short defect length (less than 1.1). For the long defect length, the Shell-92 model gives the highest failure probabilities (PF) while the B31G gives the lowest.

From the Fig. 4, it is noted that the normalized defect length is getting smaller if pipe diameter and thickness of pipeline are larger and defect length is smaller. Eventually, we can bring down the failure probabilities. However, since the pipelines with infinitely large diameter and thickness cannot be used, it is recommended to select a pipeline of proper size with consideration of the pipeline efficiency such as the pipe flow.

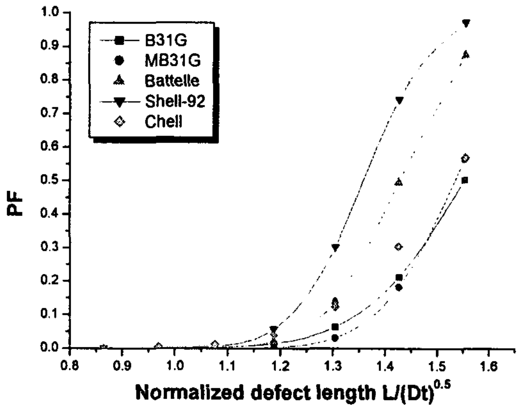
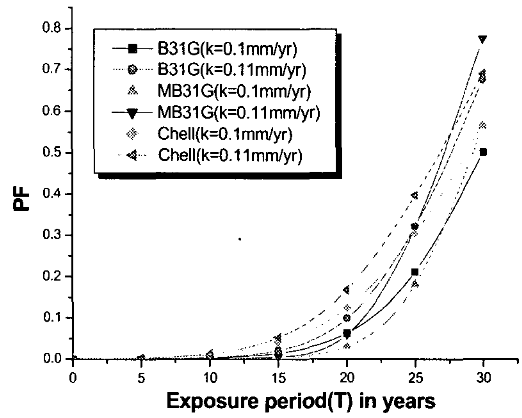
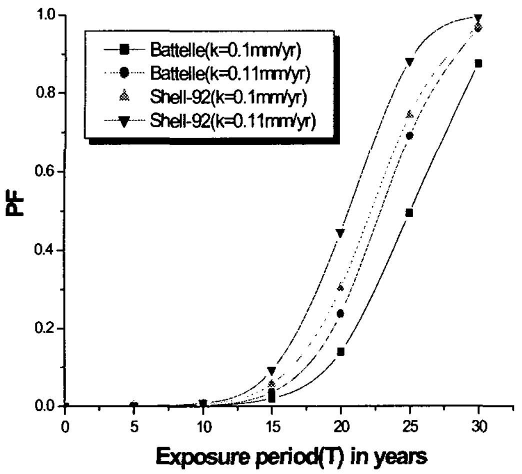


Fig. 4 A relationship between failure probability(PF) and normalized defect length $L/(Dt)^{0.5}$ for several failure pressure models

Fig. 5 shows the relationship between the failure probability and the exposed period in year for the buried pipelines under corrosion rates are both 0.1mm/yr and 0.11mm/yr. It is noted from Fig. 5 (a) that the difference of failure probability of MB31G model is larger than those of B31G model and Chell model under the corrosion rates of 0.1mm/yr and 0.11mm/yr, respectively. Because the corrosion rate is usually varied according to the place where the pipeline buried, it is recommended to select a proper pipe material with consideration of chemical condition of underground soil.



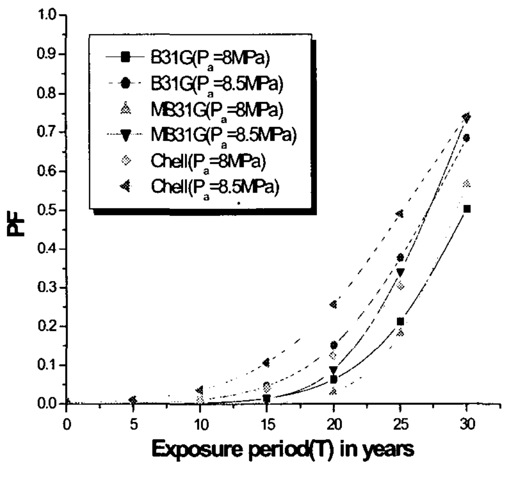
(a)



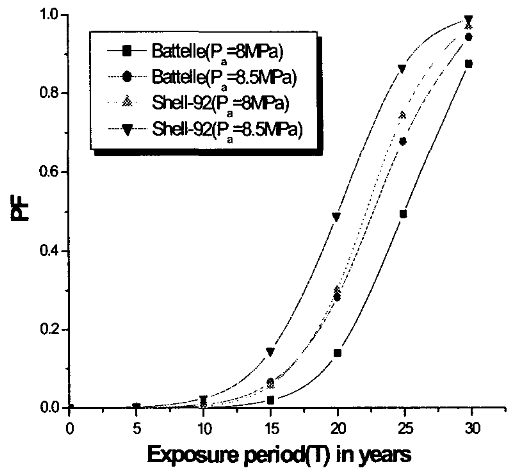
(b)

Fig. 5 A relationship between failure probability(PF) and exposure period(T) for varying corrosion rate of several failure pressure models (a) B31G, MB31G and Chell model, (b) Battelle and Shell-92 model

Fig. 6 shows the relationship between the failure probability and the exposed period in year, under the conditions of the operation service inner gas pressures of both 8MPa and 8.5MPa. It is recognized that the failure probabilities of each failure pressure model with respect to the exposed period increase uniformly.



(a)



(b)

Fig. 6 A relationship between failure probability(PF) and exposure period(T) for varying operating pressure of several failure pressure models (a) B31G, MB31G and Chell model, (b) Battelle and Shell-92 model

From Fig. 6 (a), it is also noted that the failure probabilities of the Chell model with an operation service inner gas pressure of 8.5MPa started to increase as compared with the other models in lower exposed period. And from Fig. 6 (b), the failure probabilities of Shell-92 model with an operation service inner gas pressure of 8MPa are similar to those of Battelle model with the same operation service inner gas pressure.

7. Conclusion

In this study, a failure probability model is utilized to extract useful technical information in carrying out the effective failure control for the corrosion pipeline. Using various existing failure models, the effect of the corrosion depth and length, the thickness, the diameter, the inner fluid pressure, the yield stress, material ultimate tensile strength and the corrosion rate of pipeline on the failure probability is systematically studied and the following results are obtained;

1) It is found that the thickness, diameter, material

ultimate tensile strength and the yield stress of pipeline highly affect the probability of failure and especially the effect of the variation of thickness among others is found to be more pronounced than any other parameters. Therefore, it is recommended that a different corrosion tolerance corresponding to the appropriate environment should be taken.

2) The failure pressure models give similar pipeline failure probabilities for relatively short exposure period. For long exposure periods, the Shell-92 model gives the highest probabilities of failure while the B31G gives the lowest.

3) The rate of the corrosion is generally known to be dependent on the environmental condition such as the location of pipeline setting. It is noted that the increase of the rate of corrosion makes the PF increase rapidly. Therefore, the increase of PF can be more effectively controlled by the suppression of the corrosion rate than the decrease of the corrosion rate.

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