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Reliability Estimation of Buried Gas Pipelines in terms of Various Types of Random Variable Distribution

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This paper presents the effects of corrosion environments of failure pressure model for buried pipelines on failure prediction by using a failure probability. The FORM (first order reliability method) is used in order to estimate the failure probability in the buried pipelines with corrosion defects. The effects of varying distribution types of random variables such as normal, lognormal and Weibull distributions on the failure probability of buried pipelines are systematically investigated. It is found that the failure probability for the MB31G model is larger than that for the B31G model. And the failure probability is estimated as the largest for the Weibull distribution and the smallest for the normal distribution. The effect of data scattering in corrosion environments on failure probability is also investigated and it is recognized that the scattering of wall thickness and yield strength of pipeline affects the failure probability significantly. The normalized margin is defined and estimated. Furthermore, the normalized margin is used to predict the failure probability using the fitting lines between failure probability and normalized margin.

Key Words : Buried Pipeline, Reliability Estimation, Failure Probability, FORM (first order reliability method), Normal, Lognormal and Weibull Distributions, Corrosion, Failure Pressure Model, Normalized Margin

1. *Introduction*

The technique to predict pipeline failure due to corrosion damage is necessary to determine the corrosion tolerance when we design pipelines, because the buried pipelines transporting gas and oil are usually laid underground and exposed to various corrosive boundary conditions. It seems to be an inevitable technical information to assess the safety life of aging pipelines. Therefore, systematic investigations including damage and the failure of pipelines corresponding to various corrosion environments are necessary.

The buried pipelines usually have various types of defects such as corrosion and environment-assist-cracking. The prediction of the remaining strength of pressurized pipelines containing corrosion defects is frequently carried out using deterministic methods. These methods use the nominal values for both load and the resistance parameters. However, it is well known that the load and resistance parameters have uncertainties which result from the measurement of the dimensions of defects, the manufacture of the pipe and the operating conditions of pipelines, etc.

So the failure analysis should be carried out with the help of the probability method than the

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conventional deterministic approach (CDA) because the CDA leads to uncertainties in the failure analysis with random variables imposed on various corrosion environments (Choi, 2000 ; Lee and Pyun, 2002 ; Hopkins and Jones, 1992).

In this paper, the FORM (first order reliability method) is used in order to estimate the probability of failure in the buried pipelines with corrosion defects. This method investigates the failure probability of buried pipelines using the first order Taylor series expansion of the LSF (limit state function). The effects of varying distribution types of variables such as the normal, lognormal and Weibull distributions on the failure probability of buried pipelines are systematically investigated using the FORM for the corroded pipeline.

2. Failure Pressure Models

The major factors for 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 corroded pipeline, we need to simplify the geometry of the vicinity of corroded part. Fig. 1 shows a corrosion model and is generally further simplified as shown in Fig. 2 to analyze the given geometric configuration easily. The uncertainty from simplifying of corrosion defects has not been considered in this paper, because the ANSI/ASME B31G code has taken care of the uncertainty of idealized corrosion defects shown in Fig. 2.

2.1 ANSI/ASME B31G

A failure equation for the corroded pipelines is proposed by means of the data of bursting experiment and expressed with consideration of two conditions below. First, the maximum hoop stress can't exceed the yield strength of material. Second, relatively short corrosion is projected on the shape of parabola and long corrosion is projected on the shape of rectangular. The failure

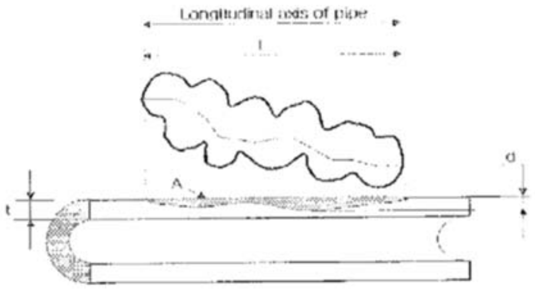
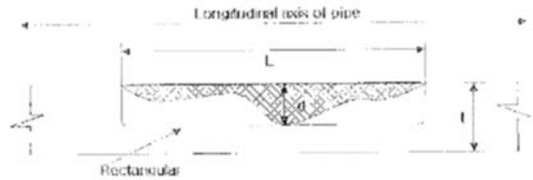


Fig. 1 A simplification of a corroded surface flaw in a pipeline

(a) Parabola



(b) Rectangular

Fig. 2 Section through an idealized corrosion defect

pressure equation for the corroded pipeline is classified by the shape of parabola and rectangular as shown below (Ahammed, 1998).

$$P_f = 1.11 \frac{2\sigma_{yield} t}{D} \left[\frac{1-(2/3)(\eta T/t)}{1-(2/3)(\eta T/t)/M} \right] \tag{1}$$

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

$$P_f = 1.11 \frac{2\sigma_{yield} t}{D} \left[1-(\eta T/t) \right] \tag{2}$$

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

where P_f is the failure pressure, D is the outer diameter, M is the bulging factor, t is the thickness of pipelines, η is the corrosion rate of 0.3 in this paper, T is the time, L is the defect length of corrosion region and σ_{yield} is the yield strength.

The bulging factor (M) is defined as below.

$$M=\sqrt{1+0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)} \quad \left(\text{for } \sqrt{0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)}\leq 4\right) \tag{3}$$

$$M=\infty \quad \left(\text{for } \sqrt{0.8\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)}>4\right) \tag{4}$$

2.2 MB31G (Modified B31G)

Kiefner and Vieth pointed out some problems on the definition of flow stress ($\bar{\sigma}=1.11\sigma_{yield}$) and bulging factor, and proposed a new flow stress such as $\bar{\sigma}=\sigma_{yield}+69$ (MPa) and a new bulging factor as follows (Kiefner and Vieth, 1990).

$$P_f=\frac{2(\sigma_{yield}+69)}{D}\left[\frac{1-0.85(\eta T/t)}{1-0.85(\eta T/t)/M}\right] \tag{5}$$

$$M=\sqrt{1+0.6275\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)-0.003375\left(\frac{L}{D}\right)^4\left(\frac{D}{t}\right)^2} \quad \left(\text{for } \left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)\leq 50\right) \tag{6}$$

$$M=3.3+0.032\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right) \quad \left(\text{for } \left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)>50\right) \tag{7}$$

3. Failure Probability

We initially assume that every variable is normal distribution and the probability distribution is determined by its mean and standard deviation. The failure probability is calculated using the FORM that is one of the methods utilizing reliability index. The FORM method is denoted from the fact that it is based on a first-order Taylor series approximation of the LSF which is defined as below (Lee and Pyun, 2002).

$$Z=R-L \tag{8}$$

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. In this paper, R indicates the failure pressure estimated by Eqs. (1), (2) and (5), and L indicates the constant operating pressure.

The event of failure occurs when $R<L$, that is $Z<0$. The probability of failure (PF) is given as below.

$$\begin{aligned} PF&=P[Z<0] \\ &=\int_{-\infty}^{0}\frac{1}{\sigma_Z\sqrt{2\pi}}\exp\left\{-\frac{1}{2}\left(\frac{Z-\mu_Z}{\sigma_Z}\right)^2\right\}dZ \\ &=\int_{-\infty}^{-\beta}\frac{1}{\sqrt{2\pi}}\exp\left\{-\frac{U^2}{2}\right\}dU=\Phi(-\beta) \end{aligned} \tag{9}$$

where μ_Z and σ_Z are the mean and standard deviation of variable Z, respectively, new variable U is $U=(Z-\mu_Z)/\sigma_Z$, Φ is the cumulative distribution function for a standard normal variable and β is the safety index or reliability index denoted as below.

$$\beta=\frac{\mu_Z}{\sigma_Z}=\frac{\mu_R-\mu_L}{\sqrt{\sigma_R^2+\sigma_L^2}} \tag{10}$$

Rackwitz and Fiessler proposed a method to estimate the reliability index using the procedure as shown in Fig. 3. In this paper, we iterated the loop shown in Fig. 3 to determine a reliable reliability index until it converges to a desire value ($\Delta\beta\leq 0.001$) (Mahadevan and Haldar, 2000).

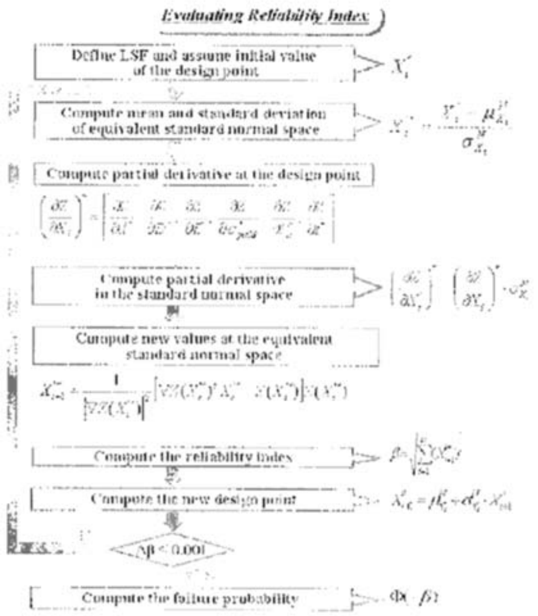


Fig. 3 Process to determine the reliability index

Where the coefficient of variation (C.O.V) is denoted as below with the standard deviation, σ_Z and the mean, μ_Z.

$$C.O.V=\frac{\sigma_Z}{\mu_Z} \tag{11}$$

4. Non-Normal Distributions

4.1 Rackwitz-fiessler transformation method

For the case of non-normal distribution of random variables, Rackwitz and Fiessler proposed the equivalent normal distribution with 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, we obtain the followings (Mahadevan and Haldar, 2000).

$$\begin{aligned} F_X(x^*) &= \Phi\left(\frac{x^*-\mu_X^N}{\sigma_X^N}\right) \\ \mu_X^N &= x^*-\Phi^{-1}(F_X(x^*))\,\sigma_X^N \end{aligned} \tag{12}$$

where Φ is the cumulative distribution function of the standard normal variable, μ_X^N and σ_X^N are the mean and the standard deviation of the equivalent normal variable at the checking point, respectively and $F_X(x^*)$ is the cumulative distribution function of the original non-normal random variables. Equating PDF (probability density function) of the original variable and equivalent normal variable at the checking point, we obtain the followings.

$$\begin{aligned} f_X(x^*) &= \frac{1}{\sigma_X^N}\phi\left(\frac{x^*-\mu_X^N}{\sigma_X^N}\right) \\ \sigma_X^N &= \frac{\phi|\Phi^{-1}(F_X(x^*))|}{f_X(x^*)} \end{aligned} \tag{13}$$

where ϕ is the PDF of the standard normal variable and $f_X(x^*)$ is the PDF of the original non-normal random variables. The non-normal variables can be treated as normal distributed variables through the transformation of Eqs. (12) and (13).

4.2 Normal and standard normal distribution

One of the most commonly used distributions in engineering problems is the normal distribution. They are symmetric with data more concentrated in the middle than in the tails. The shape of a normal distribution can be specified mathematically in terms of two parameters: the mean (μ_Z) and standard deviation (σ_Z) of random variable Z. The standard normal distribution is a normal distribution with a mean of "0" and a standard deviation of "1". Normal distributions can be transformed to standard normal distributions by the formula:

$$S=\frac{Z-\mu_Z}{\sigma_Z} \tag{14}$$

where Z is the original random variable, μ_Z is the mean of the original normal distribution and σ_Z is the standard deviation of original normal distribution. The PDF, relationship among parameters, means and variances of the lognormal distribution are presented in Table 1 (Mahadevan and Haldar, 2000).

4.3 Lognormal distribution

In many engineering problems, a random variable can't have negative values due to the physical aspects of the problem. In this situation, modeling the variable as lognormal, that is considering the natural logarithm of the variable X, is more appropriate, automatically eliminating the possibility of negative values. If a random variable has a lognormal distribution, then its natural logarithm has a normal distribution. The lognormal distribution is commonly used for general reliability analysis, cycle-to-failure in fatigue, material strength and loading variable in probabilistic design. λ and ς are the two parameters which are characterizing the lognormal distribution. The PDF, relationship among parameters, means and variances of the lognormal distribution are presented in Table 1 (Mahadevan and Haldar, 2000).

Table 1 Characteristic of varying distributions*

Distribution	Normal Distribution
PDF	$f_Z(x)=\frac{1}{\sigma_Z\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{x-\mu_Z}{\sigma_Z}\right)^2\right]$
Parameter	$\mu_Z,\ \sigma_Z$
Mean, Variance	$E=\mu_Z,\ Var=\sigma_Z^2$
Distribution	**Lognormal Distribution**
PDF	$f_Z(x)=\frac{1}{\varsigma x\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{\ln x-\lambda}{\varsigma}\right)^2\right]$
Parameter	$\lambda,\ \varsigma$
Mean, Variance	$E=\exp\left(\lambda+\frac{1}{2}\varsigma^2\right),\ Var=E^2(e^{\varsigma^2}-1)$
Distribution	**Weibull Distribution**
PDF	$f_Z(x)=\left(\frac{m}{c}\right)\left(\frac{x}{c}\right)^{m-1}\exp\left[-\left(\frac{x}{c}\right)^m\right]$
Parameter	$m,\ c$
Mean, Variance	$E=c\Gamma\left(1+\frac{1}{m}\right)$ $Var=c^2\left[\Gamma\left(1+\frac{2}{m}\right)-\Gamma^2\left(1+\frac{1}{m}\right)\right]$

* E is the mean, Var is the variance and $\Gamma(\ )$ is the gamma function

4.4 Weibull distribution

The Weibull distribution is commonly used to describe material strengths and time to failure of electronic and mechanical devices and components. The Weibull distribution may be classified as the two-parameter and three-parameter distributions. In this paper, we take the two-parameter Weibull distribution and systematically investigate the effect of two-parameter Weibull distribution of variable on the failure probability of buried pipelines. The shape parameter, m and the scale parameter, c are the two values which are characterizing the two-parameter Weibull distribution. The PDF, relationship among parameters, means and variances of the two-parameter Weibull distribution are presented in Table 1 (Mahadevan and Haldar, 2000).

5. Normalized Margin

Mechanical and structural engineers have long used safety factors to prevent failures in service. During the early part of the twentieth century, there was increasing interest in replacing traditional practices with rational design procedures. A significant breakthrough in these efforts was the assessment of the strength of cables for the Golden Gate Bridge by Freudenthal (Hecht, 2004). He examined test records and found that the tensile strength of the cables had a Gaussian distribution and therefore the knowledge of the mean strength and standard deviation permitted calculation of the failure probability under any given value of load.

The normalized margin, NM, is denoted in Eq. (15). The normalized margin has a negative value, because the strength is always greater than the load.

$$NM=\frac{L-R}{\sigma_R} \tag{15}$$

where L is the mean of load, R is the mean of resistance and σ_R is the standard deviation of resistance.

It is not easy for the workers at real field to calculating the failure probability using above process. On the other hand, they can calculate the normalized margin easily. If the relationship between failure probability and normalized margin exists, the workers of real field obtain the failure probability after they calculate the normalized margin. In this paper, we investigate the relationship between failure probability and normalized margin systemically and present the results on a graph.

6. Case Stduy

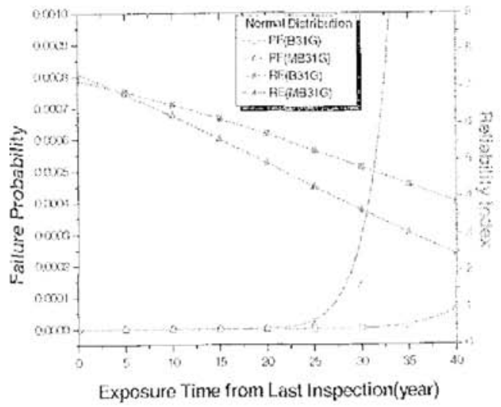
The random variables listed in Table 2 have been utilized to estimate the failure probability of the corroded pipeline (Ahammed, 1998).

Table 2 Random variables and their parameters used in the case study

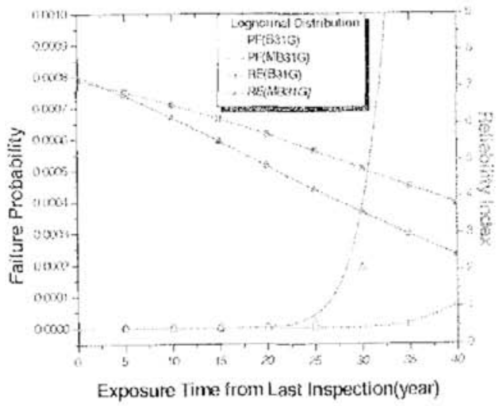
Variable	Mean	C.O.V
P_a	5 MPa	0.1
σ_{yield}	423 MPa	0.067
t	10 mm	0.05
d	3 mm	0.1
L	200 mm	0.05
D	600 mm	0.03

7. Results and Discussions

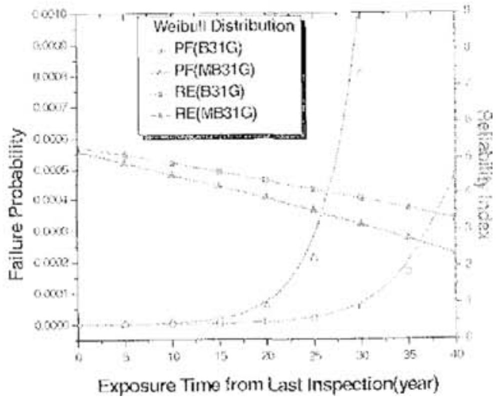
Fig. 4 shows the failure probability and reliability index with exposure time of corroded pipelines using variables in Table 2.



(a) Normal distribution



(b) Lognormal distribution



(c) Weibull distribution

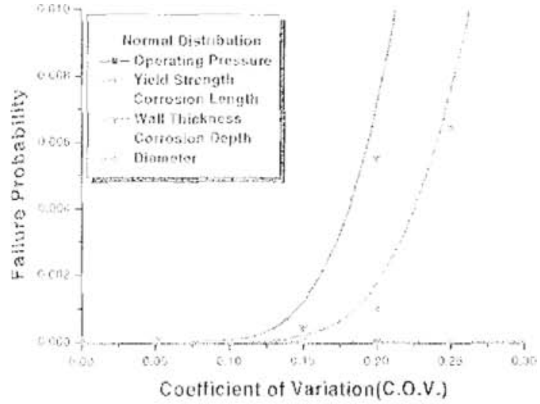
Fig. 4 Relationship between failure probability and exposure time with varying distributions

It can be recognized in Fig. 4 that the failure probability (PF) increases and reliability index (RE) decreases with increasing of exposure periods for each distribution of variables. And it is noted that the failure probability of MB31G model is larger than those of B31G model. It is found in Figs. 4(a) and 4(b) that the difference of failure probability between normal and lognormal distribution is very small. But it is found in Figs. 4(a) and 4(c) that the difference of failure probability between normal and Weibull distribution is larger than those between normal and lognormal distribution.

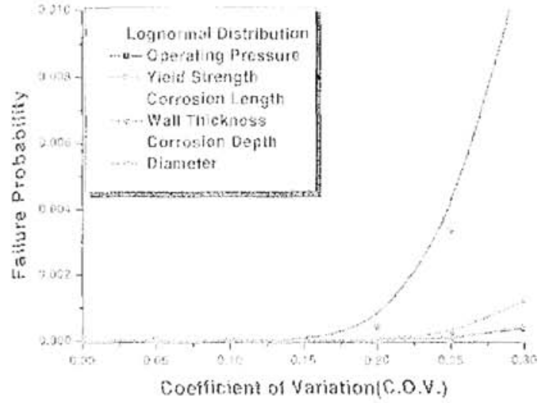
For the B31G model, it is recognized that the failure probability of lognormal distribution is about 1.55×E-05(27.9%) larger than those of normal distribution, when the exposure time from last inspection is 40-year. And the failure probability of Weibull distribution is about 4.19×E-04(755%) larger than those of normal distribution, when the exposure time from last inspection is 40-year. But for the MB31G model, it is recognized that the failure probability of lognormal distribution is about 9.04×E-04(12.4%) larger than those of normal distribution, when the exposure time from last inspection is 40-year. And the failure probability of Weibull distribution is about 2.35×E-03(32.2%) larger than those of normal distribution, when the exposure time from last inspection is 40-year.

It is found that Weibull distribution has the largest increasing rate of failure probability and the normal distribution has relatively smallest increasing rate. And the lognormal distribution has similar failure probability with normal distribution. For the B31G model, the failure probability increases rapidly after about 35-year (17% larger than Weibull distribution) exposure time, in case of the normal and lognormal distribution, and increases rapidly after about 30-year exposure time, in case of the Weibull distribution. However, for the MB31G model, the increasing rate of the failure probability becomes larger after about 25-year (17% smaller than Weibull distribution) exposure time, in case of the normal and lognormal distribution, and after about 20-year exposure time, in case of the Weibull distribution.

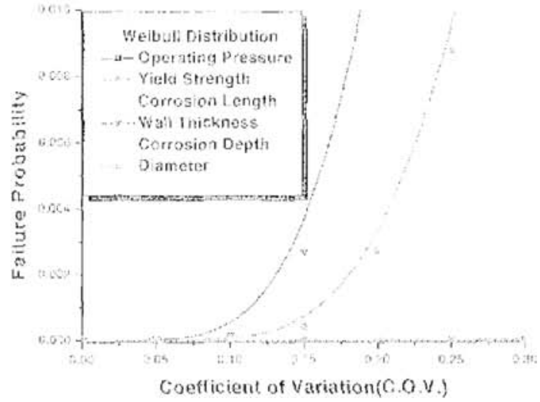
Fig. 5 shows the failure probability and reliability index with varying coefficient of variation



(a) Normal distribution



(b) Lognormal distribution



(c) Weibull distribution

Fig. 5 Relationship between failure probability and coefficient of variation (C.O.V.) with varying distributions for B31G model

(C.O.V.) for distribution types of random variable of B31G model. The meaning of having larger C.O.V. is that the distribution of variable is more scattered from the mean value. It is noted in Figs. 5(a) and 5(c) that the scattering of the wall thickness and yield strength of pipeline affects the failure probability significantly, if all of input variables have normal and Weibull distributions. That is, the effects of data scattering characteristic of wall thickness and yield strength of pipeline on the failure probability seem to be most significant.

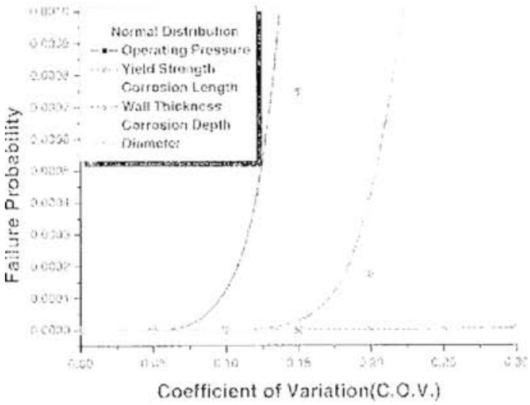
On the other hand, it is noted in Fig. 5(b) that the effect of the scattering of the operating pressure and diameter of pipeline on the failure probability is much pronounced, if all of input variables have lognormal distribution.

Fig. 6 shows the failure probability and reliability index with varying C.O.V. for distribution types of random variable of MB31G model. It is noted in Figs. 6(a) and 6(c) that the scattering of the wall thickness and yield strength of pipeline affects the failure probability significantly as similar to B31G model, if all of input variables have normal and Weibull distributions.

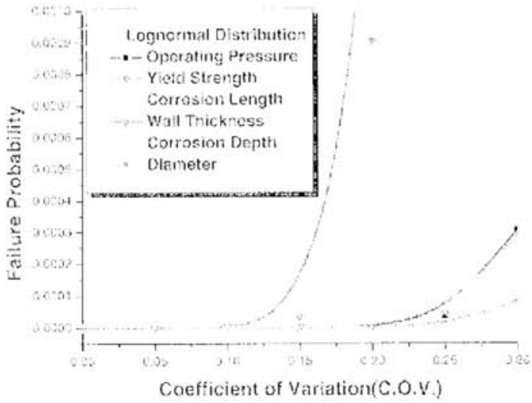
On the other hand, it is noted in Fig. 6(b) that the effect of the scattering of the operating pressure and diameter of pipeline on the failure probability is much pronounced, if all of input variables have lognormal distribution.

Figs. 7 and 8 show the normalized margin and failure probability for B31G and MB31G models, respectively. Figs. 7(a) and 8(a) show the relationship between normalized margin and failure probability on linear-scale. And Figs. 7(b) and 8(b) show the relationship between normalized margin and failure probability on log-scale. The best fitting lines for three distribution types of data for B31G and MB31G models are also shown in Figs. 7(c) and 8(c).

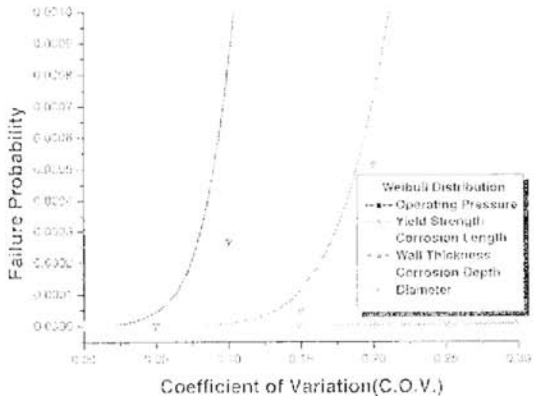
The polynomial equation is used to fit the data with a line. The highest order of a polynomial equation is selected when the standard deviation between fitting lines and data has minimum value. The standard deviations for varying polynomial equation are presented in Table 3. For B31G model, order of polynomial equation is three for normal distribution, four for lognormal distribution and three for Weibull distribution are found to be good. And for MB31G model, order of three for normal distribution, seven for both lognormal and Weibull distributions are found to be good. The equations for the fitted line are shown in



(a) Normal distribution

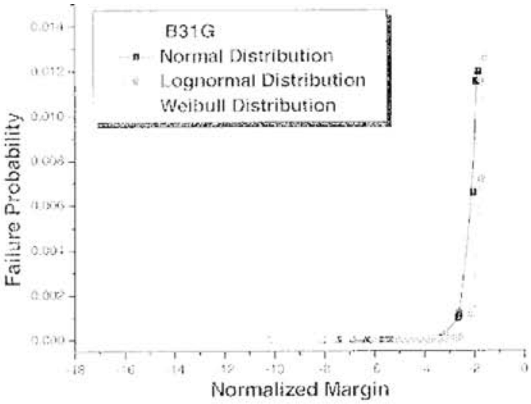


(b) Lognormal distribution

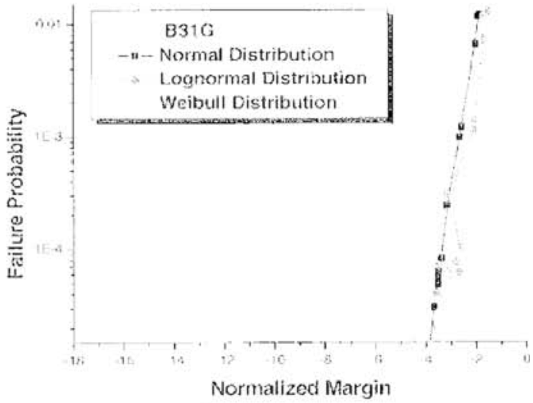


(c) Weibull distribution

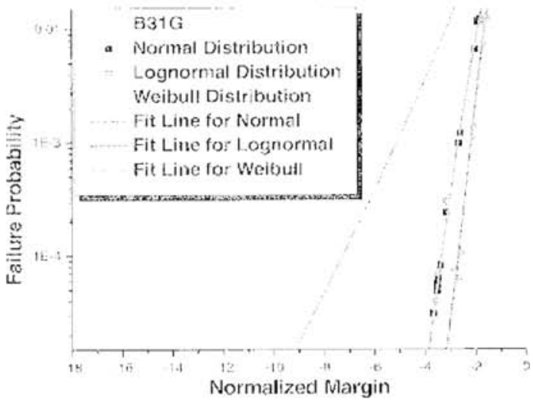
Fig. 6 Relationship between failure probability and coefficient of variation (C.O.V.) with varying distributions for MB31G model



(a) Linear scale



(b) Log-scale

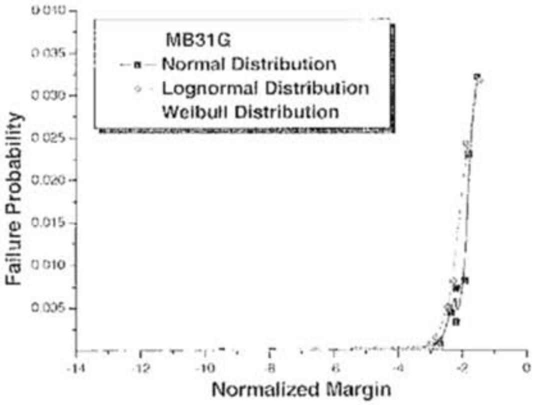


(c) Fit line with log-scale

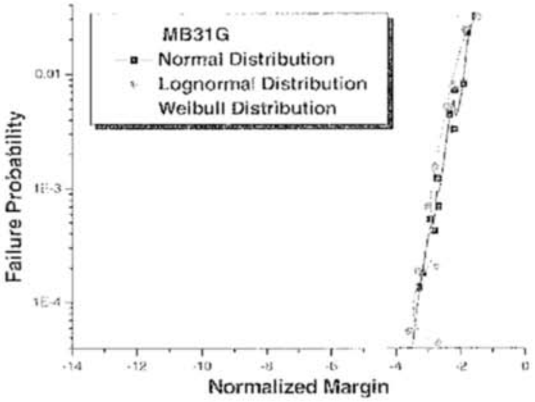
Fig. 7 Relationship between failure probability and normalized margin with varying distributions for B31G model

Table 4.

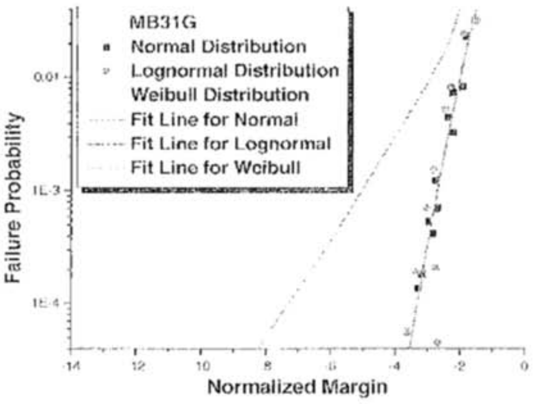
It is noted in Figs. 7 and 8 that the rates of failure probability for normal and lognormal distributions with varying normalized margin increase with similar manner. But the increasing



(a) Linear-scale



(b) Log-scale



(c) Fit line with log-scale

Fig. 8 Relationship between failure probability and normalized margin with varying distributions for MB31G model

Table 3 Standard deviation for varying orders of polynomial equation

	order	Distribution types		
		normal	lognormal	Weibull
B31G	1	0.1766	1.3222	0.1030
	2	0.1391	1.0033	0.1015
	3	0.0939	0.8884	0.0932
	4	0.0954	0.8872	0.0945
	5	0.0970	0.8959	0.0960
	order	Distribution types		
		normal	lognormal	Weibull
MB31G	1	0.2512	1.4073	0.1978
	2	0.1223	1.2646	0.1940
	3	0.1018	1.2463	0.1535
	4	0.1028	1.1980	0.1268
	5	0.1045	1.1868	0.1084
	6	0.1059	1.1238	0.1064
	7	0.1076	1.0992	0.1061
	8	0.1087	1.1204	0.1080

Table 4 The equations of fitting line in the Figs 7 (c) and 8(c) for $-14 < M0$*

	Parameter	Distribution types		
		normal	lognormal	Weibull
B31G	a	−0.5945	−7.2316	−0.1658
	b	0.2472	−11.6822	0.6409
	c	−0.2861	−7.9875	0.0202
	d	−0.0168	−2.0131	6.29E-04
	e	0	−0.1833	0
	Parameter	Distribution types		
		normal	lognormal	Weibull
MB31G	a	−0.1084	709.57	4.0605
	b	0.5321	1832.26	6.3853
	c	−0.2330	1951.94	3.0408
	d	−0.0117	1115.03	0.8283
	e	0	369.44	0.1293
	f	0	71.186	0.0116
	g	0	7.4039	5.55E−04
	h	0	0.3214	1.10E−05

* $PF = a + bNM + cNM^2 + dNM^3 + eNM^4 + fNM^5 + gNM^6 + hNM^7$

rate of failure probability for Weibull distribution with varying normalized margin is found to be smaller than those of normal and lognormal distributions. And it is found in Figs. 7(a) and 8(a) that for the B31G and MB31G models, the failure probability rapidly increases for normal and lognormal distributions, if normalized margin is larger than about −3. But the same trend is found for Weibull distribution with the normalized margin larger than about −5 for B31G model and about −4 for MB31G model, respectively.

8. Conclusions

In this paper, the FORM (first order reliability method) and the failure pressure model are utilized to extract useful technical information in carrying out the effective failure control for the corroded pipeline. Using the B31G and the MB31G models, the effects of distribution types of variables such as normal, lognormal and Weibull distributions on the failure probability are systematically studied and the following results are obtained :

(1) It is noted that the Weibull distribution has the largest failure probability and smallest reliability index. On the other hand, the normal distribution has the relatively smaller failure probability and reliability index. And the lognormal distribution has the similar failure probability to that of the normal distribution.

(2) The failure probability for the MB31G model is larger than that for the B31G model. It is recognized that the design with an aid of the B31G model is more conservative than that of the MB31G model.

(3) For the B31G and the MB31G models, the scattering of the wall thickness and yield strength of pipeline affects the failure probability significantly, if all of input variables have normal and Weibull distributions. But the effect of the scattering the operating pressure and diameter of pipeline on the failure probability is much pronounced, if all of input variables have lognormal distribution.

(4) The failure probability for normal and lognormal distributions with varying normalized margin increases with similar manner. But the increasing rate of failure probability for Weibull distribution with varying normalized margin is found to be smaller than those of normal and lognormal distributions. And it is suggested that the normalized margin and the failure probability may be easily estimated using the fitting line between failure probability and normalized margin.

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References

Ahammed, M., 1998, "Probabilistic Estimation of Remaining Life of a Pipeline in the Presence of Active Corrosion Defects," *Int. J. Pressure Vessels and piping*, Vol. 75, No. 4, pp. 321~329.

Choi, S. C., 2000, "Coating Flaw Prevention of Underground Buried Pipeline," *Gas Safety Journal*, Vol. 26, No. 5, pp. 25~33.

Hecht, H., 2004, *Systems Reliability and Failure Prevention*, ARTECH HOUSE.

Hopkins, P. and Jones, D. G., 1992, "A Study of the Behaviour of Long and Complex Shaped Corrosion in Transmission Pipelines," *In Proceedings of the 11th Int. Con. on Offshore Mech. and Arctic Eng.*, ASME, Vol. V, Part A, pp. 211~217.

Kiefner, J. F. and Vieth, P. H., 1990, "New Method Corrects Criterion for Evaluating Corroded Pipe," *Oil and Gas Journal*, Vol. 88, No. 32, pp. 56~59.

Lee, O. S. and Pyun, J. S., 2002, "Failure Probability of Corrosion Pipeline with Varying Boundary Condition," *International Journal of KSME*, Vol. 16, No. 7, pp. 889~895.

Mahadevan, S. and Haldar, A., 2000, Probability, *Reliability and Statistical Method in Engineering Design*, John Wiley & Sons.