ESTIMATION OF LEAK PROBABILITY IN PIPES AND PRESSURE VESSELS

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Estimation of leak probability of pipes and vessels is very important to assess the risk and the safety of industrial and power plants. There are two kinds of methods to estimate leak probability. The first is to use generic failure probability of pipes and vessels and the other is to simulate crack growth with a small initial crack or initiated cracks. In this paper the two methods were compared and discussed. In the second method, the leak probability was estimated in a pipe using the developed program for an initially existing crack. In the program crack initiation and crack growth due to fatigue or stress corrosion can be simulated based on the stress intensity factor or suitable damage parameters. The effects of initial crack size distribution, crack growth rate and the number of inspections on the leak probability were examined and discussed. It was found that since the effects of the important parameters on the leak probability of pipes and vessels are great, the accurate values of the parameters should be determined and defined in order to obtain the reasonable leak probability.

I. INTRODUCTION

Estimation of leak or burst probability of pipes and pressure vessels is important to assess the risk of equipment used in industries and power plants. There are two kinds of methods in estimating the failure probabilities. In the first method, the generic failure probability is obtained by examining the failure data of pipes and pressure vessels and next the failure probability of the interested equipment is estimated after multiplying the generic failure probability by several correction factors to consider the effects of important parameters such as operating period, environment or thickness of the equipment. In the second method, initial cracks are assumed to exist on the surfaces of pipes and vessels and crack growth simulation is performed for the cracks until leak or burst occurs. The failure probability can be calculated using Monte Carlo simulation technique.

Several works and references can be introduced for the first method. Thomas[1] introduced a method to estimate the leak and the rupture probability of pipe and vessels and Lydell[2] revisited the Thomas's approach. The failure probability of pipes and vessels can be estimated also using API RP-581 Code[3] or data bases for failure probability[4,5].

In the second method, initial surface cracks are assumed and crack growth simulation due to fatigue loading or stress corrosion cracking is performed until leak or rupture occurs. Initiated cracks during operation due to fatigue or corrosion also can be considered. Several programs were developed for the second method such as PRAISE[6], PRO-LOCA[7] and P-PIE[8] programs. In the program the effects of inspections and residual stresses on the failure probability can be considered also.

In this paper the features of the two methods were examined and discussed and the results obtained using each method were compared and discussed.

II. ESTIMATION OF LEAK PROBABILITY

II.A. Using generic probability data

One method to obtain leak or rupture probability of pipes and pressure vessels is to use the generic failure probability data of pipes and pressure vessels. Correction factors also can be used to consider the effects of important parameters such as operating period, environment or thickness of the equipment. Some generic failure data can be found in references 4, 5 and 9.

As an example of estimation model, the work done by Thomas[1] can be introduced. He wrote that leakage failure rates of pipes and vessels are typically in the range of 10^{-7} to $10^{-9}/(Q_e$ year). Here $Q_e=Q_p+50Q_w$ and Q_p and Q_w are Q values for parent material and weld zone material respectively. And Q is defined by $Q=DLt^{-2}$ where D is the mean diameter, L is the length and t is the thickness of pipes or vessels. He expressed the leak probability, P_L as the following equation:

$$P_L \sim 10^{-7} Q_e F. \qquad (1)$$

Here F is a plant age factor. When plant age is 10 years, F=1.0.

The probability of failure also can be obtained using the following equation given in API RP-581[3].

$$P_f(t) = gff \cdot D_f(t) \cdot F_{MS} \qquad (2)$$

Here $P_f(t)$ is the probability of failure, *gff* is a generic failure frequency, $D_f(t)$ is a damage factor and F_{MS} is a management system factor.

The damage factor is determined based on the applicable damage factor, such as thinning, general corrosion, stress corrosion cracking and mechanical fatigue etc. The management factor is to account for the influence of the facility's management system on the integrity of the plant equipment. If the damage factor for components subject to sulfide stress cracking is concerned, the damage factor is obtained using the following equation:

$$D_f = D_{fB}(age)^{1.1}. \qquad (3)$$

Here D_{fB} is the base value of the damage factor for sulfide stress cracking and *age* is the in-service time in years since the last inspection. The factor, D_{fB} is determined based on the number of inspections, the effectiveness of inspection and the severity index. If the susceptibility for sulfide stress cracking is high, the value of severity index becomes 100. If the susceptibility is low or none, the value of severity index becomes 1 and if medium, the value becomes 10. In this case the factor, D_{fB} ranges from 1 to 100 based on the number of inspections and the inspection effectiveness category.

II.B. Using crack growth simulation

Park et al.[8] developed a program, called P-PIE, in order to estimate the leak and burst probability of pipes based on the analysis models and equations of the current programs such as PRAISE and PRO-LOCA. The analysis procedure is as follows[8]:

(1) Assume a pre-existing crack, which follows a certain statistical distribution function.
(2) A post-service nondestructive inspection is assumed to be conducted. If the crack is detected, it is assumed to be repaired.
(3) Let current time and a time increment be t_{i-1} and Δt respectively.
(4) Include cracks initiated due to stress corrosion during Δt.
(5) Calculate the stress intensity factors considering stresses due to deadweight, pressure, restraint of thermal expansion, residual stresses, seismic stresses and vibratory stresses.
(6) Calculate the crack length increments during Δt due to fatigue loading and stress corrosion.
(7) Check if leak, big leak or burst event occurs during Δt.
(8) If any event occurs, add 1 to the occurrence number for the corresponding event.
(9) If necessary, in-service nondestructive inspection is assumed to be conducted. If the crack is detected, it is assumed to be repaired.
(10) If the time t_i ($= t_{i-1} + \Delta t$) is less than the given plant operation time, go to the step (3).
(11) If the number of simulations is not enough, go to the step (1).
(12) Calculate the probabilities of leak, big leak and burst as a function of time using the ratio of occurrence number of each event to the total simulation numbers.

In their paper[8] it was found that the initial crack depth distribution and the environmental parameters which affect the crack growth rate are very important in estimating the leak or burst probability of pipes. In this paper the important parameters are considered again.

II.B.1. Initial crack size distribution

Initial crack size, especially crack depth is a very important parameter in determining leak probability of pipes and vessels. Harris et el.[10] examined the existing crack depth distributions and concluded that the distribution proposed by

Marshall is adequate. Marshall's crack depth distribution follows an exponential distribution and the probability density function is expressed as follows:

$$f(a) = (1/\mu)\, e^{-a/\mu}. \qquad (4)$$

In Marshall's crack depth distribution, μ = 6.248 mm (0.246 in.) and μ is also the mean value of crack depth. As Harris et el.[10] indicated, Marshall's distribution is very conservative compared to other distributions. When μ = 1.702 mm (0.067 in.) in Eq. (4), best fit can be obtained with Becher and Hansen's lognormal distribution, which was obtained form 228 surface crack data. Also Marshall's distribution is adequate for pipes with thick thickness greater than 3 or 4 inches. If the thickness of a pipe is less than 3 inches, the following equations need to be used:

$$f(a) = e^{-a/\mu} / \left[\mu\left(1 - e^{-t/\mu}\right)\right]. \qquad (5)$$

Here t is the thickness of a pipe.

Khaleel et al.[11] proposed another crack depth distribution following lognormal distribution as follows:

$$f(a) = \frac{1}{\mu a\sqrt{2\pi}} e^{\frac{-[\ln(a/a_{50})]^2}{2\mu^2}}. \qquad (6)$$

Here a_{50} is the median crack depth and μ is the shape parameter. Values of a_{50} and μ are given in reference 7 for several kinds of materials and welds. For example, a_{50} and μ are given as a function of the thickness, t as follows for ferritic MMAW (manual-metal-arc weld) welds:

$$a_{50} = 0.0519t^{[-0.4572+0.04326\ln(t)]} \qquad (7)$$

$$\mu = 0.5102 + 0.2294\ln(t) \qquad (8)$$

Note that the unit of a_{50}, μ and t is inch in Eqs. (7) and (8).

II.B.2. Crack growth rate

Crack growth rate due to fatigue loading or stress corrosion cracking is also an important parameter, which gives great effects on the failure probability of pipes and vessels. Many kinds of crack growth models can be found in literatures. In this study the following crack growth model was used in stress corrosion cracking:

$$\frac{da}{dt} = \mathrm{A}\,(K - K_{th})^n. \qquad (9)$$

Here K is stress intensity factor and K_{th} is a threshold value of K. If $K < K_{th}$, a crack is not growing. The units of da/dt and K are m/s and MPa·m$^{1/2}$ respectively.

II.B.3. Inspection

Pre-service and in-service inspections can be considered in the program. When a crack is detected during an inspection, it is assumed to be repaired. Detection probability is expressed as a function of crack size. In PRAISE program[6] the following function is used:

$$P_{ND}(\mathrm{A}) = \varepsilon + \frac{1-\varepsilon}{2}\mathrm{erfc}(\nu\ \ln A/A^*) \ . \qquad (10)$$

Here P_{ND} is the probability of not detecting a crack with area, A and ε, ν and A^* are parameters to define the effectiveness of inspection.

III. CALCULATION RESULTS

Several example problems were solved and the effects of several important parameters were examined. It was assumed that one circumferential surface crack existed on the inner surface of a pipe. In the example problems, the outer diameter of the pipe is assumed to be 406.4 mm (16 inches) and the wall thicknesses are 7.9, 12.7 or 21.4 mm.

In the problems, material is assumed to be usual carbon steel for pipes. The dominant failure mechanism is stress corrosion cracking and the crack growth rate is assumed as A= 3.29 x 10^{-17}, K_{th}= 0, n= 4.0 in Eq. (9). This crack growth rate is given as the low sulfur line of the General Electric model in the reference 12. Leak probability is estimated using P-PIE program. It was assumed that the yield strength, σ_o=234 MPa, the ultimate strength, σ_u= 534 MPa and the elastic modulus, E=184 GPa for the pipe material. And α= 1.57, n= 4.59 and $\varepsilon_o = \sigma_o/E$ in the following Ramberg-Osgood relation of the considered material.

$$\frac{\epsilon}{\varepsilon_o} = \frac{\sigma}{\sigma_o} + \alpha\left(\frac{\sigma}{\sigma_o}\right)^n \qquad (11)$$

Details on the procedures and equations used in the P-PIE program can be found in the reference 8. Pre-service and in-service inspections were considered and the values of A^*= 0.25, ν = 3.0 and ε = 0.005 were used in Eq. (10). The applied stress on the crack is also very important parameter. Axial normal stress of 112.6 MPa is assumed to be applied in the pipe.

Figure 1 shows the effect of initial crack depth on the leak probability of pipe. It was assumed that the initial crack depth follows an exponential distribution. Leak probabilities were obtained for two cases when μ = 6.248 mm and μ = 1.702 mm in Eq. (4). Pre-service inspection was performed and in-service inspections were also performed every 5 years. The results were given in Fig. 1. It can be noticed that the mean value of initial crack depth give a great effect on the leak probability. So it is very important to obtain the accurate distribution of initial crack depth.

Because in-service inspection is performed every 5 years, leak probability increases during the initial 5 years. After 5 years of operation, the leak probability keeps nearly constant value. When μ = 1.702 mm, the constant value becomes 2.6E-5. This value is the leak probability for one existing crack. In order to obtain the total leak probability in pipes, the probability of crack existence should be multiplied by the value. Harris et al.[10] examined the crack frequency in welds. One typical value of crack frequency is 0.066/m for pipes and 2.1E-4/m for pressure vessels. So the number of crack in the weld with the length of 1 m is 0.066 in pipes. If we multiply 0.066 by the value 2.6E-5, the total leak probability becomes 1.72E-6/m.

Next the probability is estimated using the generic failure probability using Eq. (2) given in API RP-581 Code. If only sulfide stress cracking damage is considered and a damage of a small hole size is assumed, the value of *gff* becomes 8E-6. If the severity index is 10, the inspection effectiveness category is B and F_{MS} =1, the failure probability after 30 years of operation becomes 2.82E-4. Or if the severity index is 50, the inspection effectiveness category is C and F_{MS} =1, the failure probability after 30 years of operation becomes 1.69E-3. Since the total length of pipe lines in a plant is not given in API RP-581 Code, the two probability values cannot be compared with each other directly. The value of 1.72E-6/m obtained from P-PIE program, however, seems reasonable.

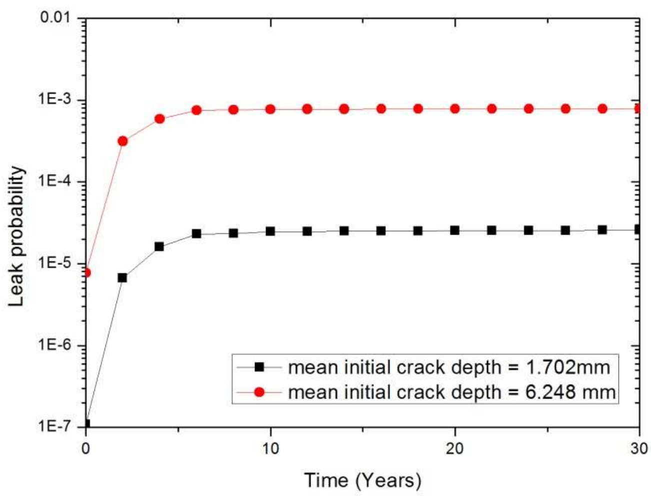

Fig. 1. Effect of the mean value of initial crack depth on the leak probability of the pipe.

Figure 2 shows the effect of the number of inspections on the probability of the pipe. It was assumed that all conditions were same as the previous problem considered in Fig. 1 except the number of inspections. Pre-service inspection was performed in all cases. From the figure it is recognized that the number of inspections gives great effect on the leak probability of pipes.

Figure 3 shows the effect of the crack growth rate due to stress corrosion. It can be noticed that the growth rate also gives great effect on the leak probability of pipes.

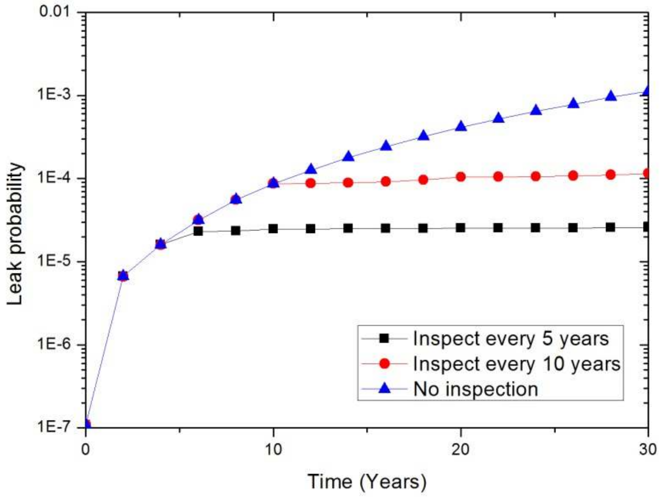

Fig. 2. The effect of the number of inspections on the leak probability of the pipe.

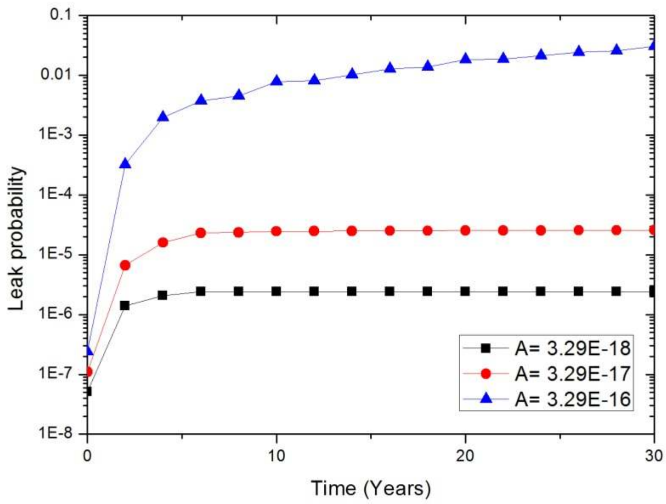

Fig. 3. The effect of the growth rate of a crack on the leak probability of the pipe.

From the results of some example problems, it can be found that the important parameters such as the initial crack depth distribution, the number of inspections and the crack growth rate give great effect on the leak probability of pipes. In order to estimate the accurate leak probability of pipes and vessels these important parameters should be known accurately. Or if the estimated leak probability needs to be used as a parameter in any regulations, the values of important parameters should be defined accurately in the analysis procedures.

II. CONCLUSIONS

Two kinds of methods to obtain the leak probability of pipes and pressure vessels were examined and discussed. The leak probability of a pipe was obtained using the P-PIE program and the effects of important parameters were examined and the following conclusions were obtained.

1. The initial crack depth distribution, the number of inspections and the crack growth rate give great effect on the leak probability of pipes.
2. Since the effects of the important parameters on the leak probability of pipes and vessels are great, the accurate values of the parameters should be determined and defined in order to obtain the reasonable leak probability.
3. The failure probability value obtained using the generic failure probability can be used in examining the accuracy of the failure probability obtained using a crack growth simulation. For this purpose, some important data, such as the total length of pipe lines and welds or the thickness of pipes, should be provided with the generic failure probability.

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