Risk-Based Considerations in Developing Strategies to Ensure Pipeline Integrity—Part II: Applications

S. Rahman

B. N. Leis
Engineering Mechanics Department,
Battelle Memorial Institute,
Columbus, OH 43201

This is the second in series of two papers generated from a recent study on risk-based analysis for developing strategies to ensure pipeline integrity. This paper (Part II—Applications) focuses on the applications of the proposed deterministic and probabilistic models presented in the first paper (Part I—Theory) (Leis and Rahman, 1994) for stochastic pipe fracture evaluations. Using these models, numerical predictions are made for line-pipe steel typically used in gas transmission pipelines and are compared with the available test data. Thereafter, the paper explores the significance of the random variables related to serviceability in pipelines subjected to flaw growth in service. The results are discussed in the light of a hydrotest-based approach to ensure pipeline integrity. It is concluded that analysis of hydrotest strategies to optimize safety for such populations (e.g., Leis and Brust, 1992) should be based on a probabilistic analysis that permits risk assessments associated with pipeline operating decisions and the type and frequency of hydrotests done to ensure continued safe operation of the line. This same probabilistic framework could be used to assess the operating and safety implications for flaw populations characterized by in-line inspection.

1 Introduction

Historically, safe operation of thousands of miles of natural gas transmission pipelines underscores the merits of hydrotesting as a means to verify the integrity of the line as constructed and to demonstrate continuing serviceability through the use of periodic retesting programs. Hydrotesting is currently the only viable means to detect and control certain types of defects, such as stress-corrosion cracking (SCC); but the evolution of the defect population with service means that the defect population at any instant in time of the pipeline is a random variable. The mechanical properties and the toughness of the pipe steel are similarly random variables along the pipeline as is the pressure loading during service. However, during hydrotesting the pressure history is closely controlled and varies only in a well-defined manner as a function of the pipeline's elevation. The variability in properties and defect population can confound decisions as to which test pressure provides the optimum balance between the number and size of defects that will be removed in the test versus the interval between hydrotests and the likelihood of an in-service failure. This variability also can complicate serviceability decisions based on in-line inspection results, which introduces the added uncertainty in the measurement of the flaw population (Leis and Rahman, 1993).

This is the second in series of two papers generated from a recent study on risk-based analysis for developing strategies to ensure pipeline integrity. This paper focuses on the predictions by the proposed deterministic and probabilistic models presented in the first paper (Leis and Rahman, 1994). Comparisons are made between the predictive results and the experimental data when available. Thereafter, the paper explores the significance of the random variables related to serviceability in pipelines subjected to flaw growth in service. The results are discussed in the light of a hydrotest-based approach to ensure pipeline integrity. It is concluded that analysis of hydrotest strategies to optimize safety and reliability (e.g., Leis and Brust, 1992) should be based on a probabilistic analysis that permits risk assessments associated with pipeline operating decisions and the type and frequency of hydrotests done to ensure continued safe operation of the line. This same probabilistic framework could be used to assess the operating and safety implications for flaw populations characterized by in-line inspection.

2 Deterministic Model Validation

Finite-element analyses have been performed to examine the validity of the assumptions used in the primary creep damage

---

Contributed by the Pressure Vessels and Piping Division for publication in the JOURNAL OF PRESSURE VESSEL TECHNOLOGY. Manuscript received by the PVP Division, September 2, 1993; revised manuscript received February 15, 1994. Technical Editor: S. Y. Zamrik.

model for surface cracks. As detailed in Leis et al. (1991) and Brust and Leis (1992; 1990), the results indicate that the assumptions and simplifications embedded in the time-marching estimation scheme provide reliable estimates of crack driving force. Further assessment of the utility of this simplified method follows here in comparisons of predictions for full-scale pipe tests. Figure 1 illustrates the utility of the deterministic model in terms of predicted and observed failure pressure for a wide range of pipeline applications. The ratio between predicted and observed failure pressures has the mean value of 1.011 with coefficient of variation less than 10 percent. Hence, the underlying deterministic model is very accurate in predicting failure pressures. Figure 2 shows the utility in terms of time-dependent flaw growth and the significance of this growth under hydrotest conditions. It presents a typical comparison of the predicted and observed flaw initiation, growth, and failure behavior on coordinates of pressure and flaw extension. Note that the flaw growth predictions are conservative with crack initiation predicted earlier than the corresponding experimental results. The predicted final crack length is slightly conservative as is the failure pressure. However, both compare reasonably well with the test results. Figure 2 shows that much of the crack growth occurs during the hold periods, which mean that neglecting time-dependent (creep) effects could lead to nonconservative predictions of crack growth and failure. Also, shown here is the failure prediction made by an empirical method developed by Kiefner et al. (1973). The method, which does not include explicit crack growth and time-dependent effects, significantly underestimates the failure pressure. Similar comparisons of observed and predicted behavior covering a wide range of flaw geometries have been made in Leis et al. (1991). In all cases, reasonably accurate predictions of failure pressure have been achieved.

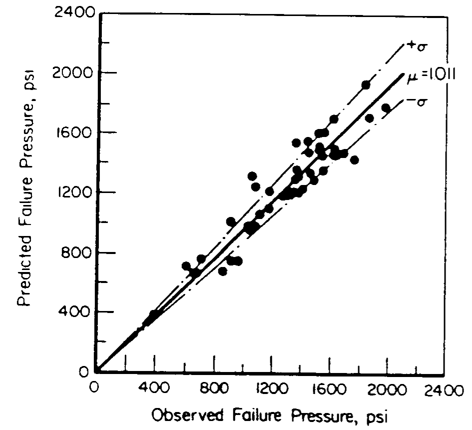

Fig. 1 Observed and predicted burst pressures for axial part-through-wall cracked line pipes for a wide variety of steel grades, pipe geometries, and flaw geometries

3 Statistical Characterization of Inputs

Fracture-mechanics variables, which are inherently random are 1) initial crack size, e.g., crack depth and length; and 2) material characteristics, e.g., stress-strain properties and toughness properties of the pipe. Service conditions (e.g., stress levels, cyclic rate, temperature, pressure, environment), particularly during a hydrotest, and pipe geometry (e.g., pipe radius and thickness) for gas transmission pipes can be accurately calculated, and, hence, they will be assumed to be deterministic.

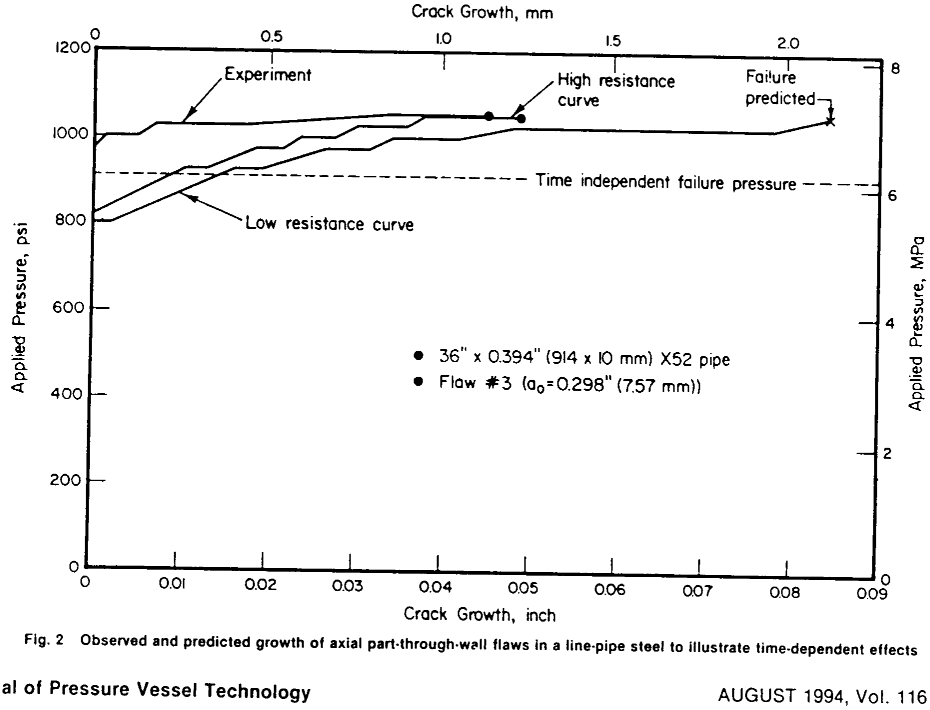

Fig. 2 Observed and predicted growth of axial part-through-wall flaws in a line-pipe steel to illustrate time-dependent effects

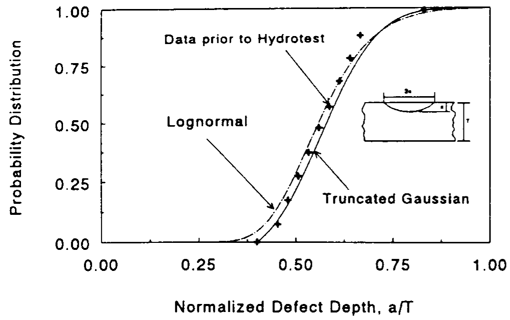

Fig. 3 Cumulative probability distribution of *a/T* prior to hydrotest

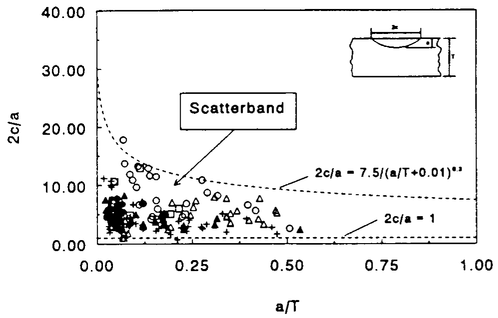

Fig. 4 Correlation between *2c/a* and *a/T* (data characteristic of SCC flaws)

Table 1 Statistical properties of random inputs

Random variable	Mean	Standard deviation	Probability distribution
a/T	0.57	0.114	Gaussian [a]
$2c/a$	$(A+B)/2$	$(B-A)/\sqrt{12}$	Uniform [b]
K_0	135.8	5.03	Gaussian
n_0	8.78	0.729	Gaussian
σ_y	65 ksi	2.73 ksi	Gaussian
σ_u	85 ksi	3.15 ksi	Gaussian
CVP	36 ft-lb	3.05 ft-lb	Gaussian

[a] Truncated with lower bound = 0.4 and upper bound = 1.0
[b] $A = 1$, $B = 7.5/(a/T+0.01)^{0.3}$

3.1 Initial Crack Size. Both pre-service and in-service inspections can provide a wealth of data from which statistical properties of the crack size can be determined. Figure 3 shows the actual field data of probability distribution of an "initial" normalized crack depth (a/T) derived from hydrotests on pipelines. These data were developed for the actual gas transmission pipelines from past research programs conducted at Battelle. It appears that a lognormal or truncated normal distribution can represent fairly well the probabilistic characteristics of a/T. Similar characterization of crack length ($2c$) or aspect ratio ($2c/a$) is more complex because it can be correlated with a/T. Figure 4 represents such a correlation showing scatter plots of actual $2c/a$ versus a/T data (characteristic of SCC flaws) from several existing pipelines. Clearly, $2c/a$ (or a/c) is random, but the amount of its scatter is also dependent on a/T. In this paper, it is assumed that $2c/a$ is uniformly distributed with its lower and upper bounds being functions of a/T (see Fig. 4). Although somewhat arbitrary, this uniform distribution is the most judicious choice since no specific pattern is observed in the histogram of $2c/a$ for such a small population of data. The statistical properties of a/T and $2c/a$ are summarized in Table 1.

3.2 Material Properties. In conducting nonlinear fracture-mechanics analyses, several analytic idealizations are considered. For example, it is assumed that the constitutive law characterizing the steel's stress-strain response can be represented by the time-dependent Ramberg-Osgood model

$$\epsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K(t)}\right)^{n(t)} \tag{1}$$

or the normalized version

$$\frac{\epsilon}{\epsilon_0} = \frac{\sigma}{\sigma_0} + \alpha(t) \left(\frac{\sigma}{\sigma_0}\right)^{n(t)} \tag{2}$$

where σ_0 is an arbitrary reference stress usually assumed to be yield stress, E is the elastic modulus, $\epsilon_0 = \sigma_0/E$ is the associated reference strain, and $K(t)$, $\alpha(t)$, $n(t)$ are time-variant, strain-hardening parameters usually chosen from a best fit of test data. Note that Eqs. (1) and (2) are equivalent if $\alpha(t) = E\sigma_0^{n(t)-1}/K(t)^{n(t)}$, which provides a means to calculate $\alpha(t)$ [or $K(t)$] when $K(t)$ [or $\alpha(t)$] and $n(t)$ are known for a given material. For typical gas transmission pipe materials, the time-dependent Ramberg-Osgood parameters also admit a multiplicative decomposition of the form (Leis et al., 1991)

$$\begin{aligned} \alpha(t) &= \alpha_0 f_1(t) \\ n(t) &= n_0 f_2(t) \\ K(t) &= K_0 f_3(t) \end{aligned} \tag{3}$$

where α_0, n_0, and K_0 are the random initial values (i.e., at time, $t = 0$) and $f_1(t)$, $f_2(t)$, and $f_3(t)$ are the deterministic time functions, which can be obtained from the isochronous test data (Leis et al., 1991). Typical functional values of f_1 and f_2 for X65 line-pipe steel are given in the companion paper (Leis and Rahman, 1994). (Note: f_3 is the dependent function and can be obtained when E, σ_0, α_0, n_0, K_0, f_1, and f_2 are known.) Also, the J-resistance from the compact tension (CT) specimens is deemed to be adequately characterized by linear equation of the form (Leis et al., 1991)

$$J_R(\Delta a) = J_{Ic} + C\Delta a \tag{4}$$

in which Δa is the extension of crack length during crack growth, J_{Ic} is the random fracture toughness at crack initiation, and $C = dJ_R/da$ is the random slope parameter from best fit of experimental data. In the absence of CT specimen data, these toughness parameters J_{Ic} (k/in) and C (k/in^2) can also be obtained from empirical correlation with full-size Charpy plateau energy, CVP (ft-lb) and flow stress, σ_f (ksi) as (Leis et al., 1991)

$$J_{Ic} = 14.92 \times 10^{-5} \sigma_f \, \text{CVP}$$

$$C = \frac{dJ_R}{da} = \frac{108.2 \sigma_f \, \text{CVP}}{E} \tag{5}$$

where $\sigma_f = (\sigma_y + \sigma_u)/2$ is the average of yield stress, σ_y and ultimate stress, σ_u. Standard statistical analyses of raw data for typical line-pipe steels (Leis and Rahman, 1993; Leis et al., 1991) indicate that K_0, n_0, and CVP, σ_y, σ_u can be modeled as independent Gaussian random variables. Table 1 shows the distribution properties of these variables that are characteristic of X65 line-pipe steel. All other parameters such as E, ν, and σ_0 are assumed to be deterministic.

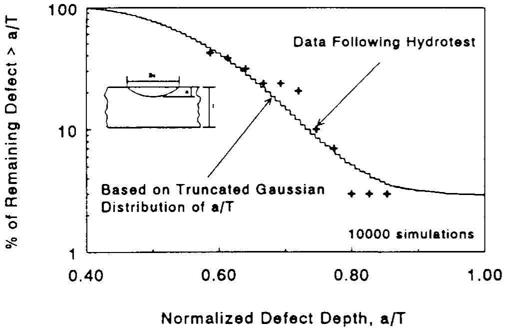

Fig. 5 Probability of crack depth at t = 24 h

4 Probabilistic Simulation of a Hydrotest

4.1 Description of the Problem. This section simulates a hydrotest on a pipe with mean radius, R = 18 in., and wall thickness, T = 0.36 in., which is subjected to a test pressure of p = 1430 psi. The pipe is made of Grade X65 steel with the deterministic properties: E = 30000 ksi, ν = 0.3, and reference stress σ_0 = 65 ksi. The random properties are: a/T $2c/a$, K_0, n_0, σ_y, σ_u, and CVP, whose probabilistic characteristics have been given in Table 1. The hydrotest on this line is simulated to determine probabilistic characteristics of several response (output) variables so that the significance of the random nature of crack geometry and material properties can be assessed. The companion paper (Leis and Rahman, 1994) provides the theoretical formulations needed to perform the numerical calculations presented here. But first the model used in this simulation is compared to service results for this same situation as the basis for its validation.

4.2 Probabilistic Validation. Once the test pressure is applied, cracks present in the line can grow. Deeper cracks in the population of sizes prior to the test can grow sufficiently to become through wall at the test pressure. Due to the random nature of the size of cracks in this initial population and the material properties, the crack depth at any instant of time during the hydrotest is also a random variable. Predictions of the response of this population to the hydrotest by the probabilistic model involve the following three steps. First, the components of the random vector constituting the uncertainty are randomly generated according to their probability distributions. Second, repeated deterministic analyses based on time-dependent elastic-plastic fracture mechanics are conducted to calculate crack size at the end of 24-h hold period. Third, standard statistical analysis is performed to calculate the probability that the crack depth is greater than a given threshold.

Figure 5 presents the validation results as a comparison of the observed and simulated percentage of cracks with a depth greater than a given size as a function of crack depth at the end of the hold period. The hydrotest had a maximum test pressure of 95 percent p_{SMYS} where SMYS denotes the specified minimum yield stress, and this pressure was held for 24 h (the actual test pressure varies by location along the line as a function of elevation). The simulated results, which include the above probabilistic characteristics, are shown in this figure as the trend. The corresponding data from the hydrotest are shown as the solid points. The close correspondence between the observed and simulated behavior for this hydrotest indicates that this probabilistic model can predict accurately the crack growth characteristics of pipelines. Note from the figure that the trend for smaller flaws is correctly represented as is the size of the flaws removed from the line. The results of Fig. 5, thus, validate the probabilistic model for pressurized pipelines.

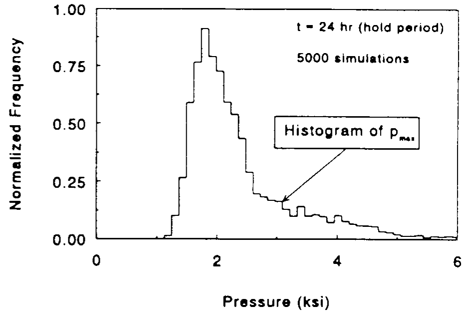

Fig. 6 Historgram of failure pressure (t = 24 h)

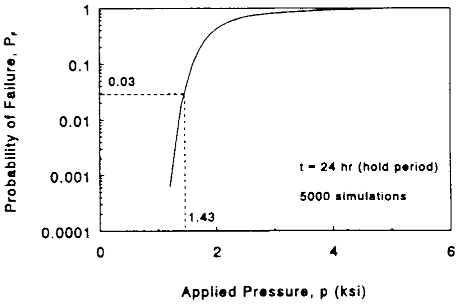

Fig. 7 Probability of failure for a given applied pressure

5 Results and Discussion of Probabilistic Hydrotest Simulations

Figure 6 shows the histogram of $p_{\max}$ (load-carrying capacity) for a 24-h hold period obtained by conducting 5000 simulations. Methods to calculate $p_{\max}$ via simulation are described in the companion paper (Leis and Rahman, 1994) and will not be repeated here. When the sample size increases indefinitely, the histogram approaches the probability density of $p_{\max}$. From this histogram (Fig. 6), it appears that the probability density function of $p_{\max}$ has a skewed shape, and hence, $p_{\max}$ should not be treated as a Gaussian variable. Also from the simulations, the mean and standard deviation of $p_{\max}$ are 2380 psi and 905 psi, respectively. Hence, the coefficient of variation is $(905/2380) \times 100$ = 38 percent, indicating significant variability of $p_{\max}$ due to uncertain input parameters. That is, the probabilistic nature of the properties causes a significant variability in the serviceability of a pipeline. Analyses that reflect the random nature of these properties, therefore, are needed to make rational decisions on serviceability and safety.

Figure 7 shows a plot of failure probability (P_F) versus applied pressure (p) using Monte Carlo simulation (MCS) presented in Leis and Rahman (1994). The probability of failure is defined as the probability that the load-carrying capacity ($p_{\max}$) of the pipeline is less than the given applied pressure (p). The failure criteria and the corresponding performance (limit-state) function are explicitly defined by Eqs. (22) and (25), respectively in Leis and Rahman (1994). Hence, Fig. 7 represents the probabilistic characteristics (cumulative probability distribution function) of the load-carrying capacity characteristic of a Grade X65 gas pipeline whose properties are as defined in Table 1. It provides a quantitative assessment of the risk of pipeline failure due to a given hydrotest pressure. For example, when the applied pressure p = 1430 psi, Fig. 7 indicates that the failure probability is 0.03. This means that

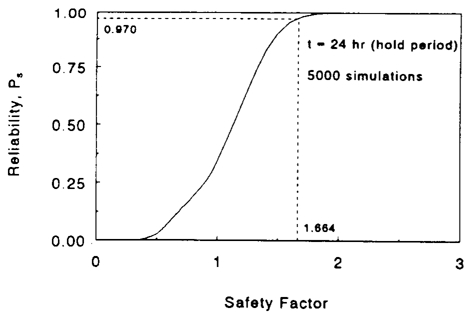

Fig. 8 Reliability for a given safety factor

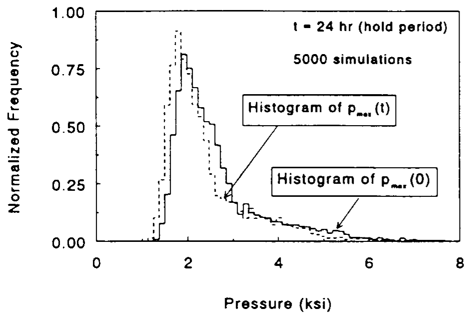

Fig. 9 Effects of creep damage on the failure pressure

when hydrotests are performed on this line, 3 out of 100 tests will exhibit failure at this test pressure. This predicted failure probability also compared very well with observed failure rate shown in Fig. 5 (tail of distribution).

Results like that shown in Fig. 7 are of great practical importance and value in selecting the pressure conditions for a hydrotest (within the applicable code requirements). Consider first the significance of the shape of the trend. Observe that the probability of failure increases initially very quickly with test pressure. This implies that significant increases in the failure rate can occur with modest increase in pressure. It also indicates that the probability that cracks will be removed by hydrotests done at lower pressure (that still satisfy code minimums) is very low, regardless of the size of the cracks. This means that there is little safety benefit derived from the investment in the testing under such conditions. At higher pressures the trend in failure rate is less sensitive to pressure. Very high pressures, however, are impractical because extensive yielding occurs.

The magnitude of the failure rate as a function of test pressure in Fig. 7 depends on the mechanical and fracture properties for the pipeline steel for the line being considered. These properties can be described in terms of their mean or average behavior and the variability of the response about that mean. Differences in the average values of different pipe steels will tend to drive the trend shown in this figure from left to right (i.e., as a function of pressure). Differences in the variability of these properties will tend to drive this trend up or down for a given pressure. It follows that the magnitude of the failure rate is dependent on the situation being addressed. The variability in properties presented in Table 1 is by definition typical of the X65 class of steels, which means that the magnitude of failure rate shown in Fig. 7 is rather typical of the response of this grade to hydrotests. However, because the mean values used to represent this steel can differ greatly within a grade of steel, the curve in Fig. 7 should be developed on a case-by-case basis.

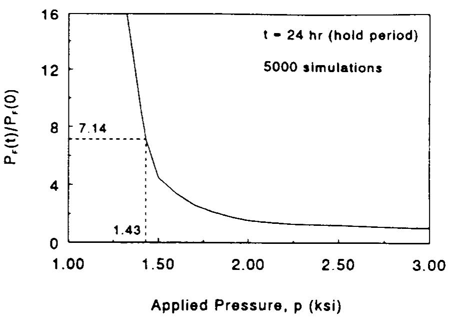

Fig. 10 Effects of creep damage on the failure probability

A method to assess safety in traditional deterministic analysis in some pipeline companies involves the use of safety-factor analysis. Although defined in different ways, safety factors are introduced to address qualitatively the variability of input parameters. For purposes of the present discussion, the safety factor is defined by the ratio of mean value of $p_{\max}$ and actual applied pressure, p. The mean value of $p_{\max}$ can be calculated from probabilistic analysis as done here or it can be approximately estimated by performing a deterministic analysis based on the average values of input.

Figure 8 shows the variation of pipeline reliability, P_S ($P_S = 1 - P_F$) as a function of the safety factor. Note from this figure that a significant limitation of deterministic-safety-factor analysis, the absence of quantitative correlations with risk or probability of failure, is avoided within a probabilistic framework. Figure 8 shows that for the hydrotest of concern, the actual safety factor is 2380/1430 = 1.664. The corresponding reliability and failure probability are 0.97 and 0.03, respectively. Using the figure, it can be shown that an increase or a decrease in the test pressure by 10 percent (from 1430 psi) increases or decreases the pipeline probability of failure by 192 and 88 percent, respectively, thus indicating strong dependence of safety on the test pressure. These results underscore the considerable attention to be given for selecting test pressures and emphasizes the benefits of a probabilistic framework that provides the corresponding risk of failure.

Figure 9 presents results that illustrate the effects of the pressure-hold-induced primary creep crack growth on the failure pressure ($p_{\max}$) for the hydrotest simulated above. Creep occurs at the crack tip because of the very high localized stresses. This is not the same physical process that occurs at high temperatures. Note from Fig. 9 that two trends are presented: that marked as $p_{\max}(0)$ denotes the response without the creep crack growth due to the hold (the continuous trend), while that denoted $p_{\max}(t)$ includes the creep crack growth (the broken trend). The effect of the creep crack growth is evident in this figure in the shift of the probability mass in the histogram towards the left (lower loads), indicating a loss of pressure capacity of the pipeline. Correspondingly, the mean value of $p_{\max}$ changes from 2650 psi to 2380 psi, indicating a 10-percent reduction of mean failure pressure.

More dramatic effects of time-dependent damage are evident in Fig. 10, which corresponds to Fig. 9 in terms of failure probability. This figure plots $P_F(t)/P_F(0)$ (probability of failure including creep crack growth over the 24-h hold divided by that without a hold time) versus applied pressure for a hold period of t = 24 h. For a pressure of 1430 psi, the foregoing ratio $P_F(t)/P_F(0)$ read from this figure is 7.14. Thus, there is a significant dependence of failure probability on the time-

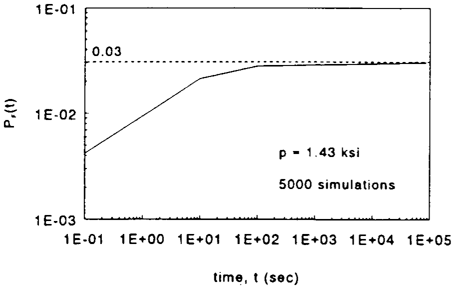

Fig. 11 Time evolution of failure probability for p = 1430 psi

dependent creep cracking. This sevenfold increase is to be expected because the creep drives the failure process that removes the cracks at typical test pressures. As with the other plots that show pressure on the abscissa, Fig. 10 indicates that pressures higher than typical burst pressures for pipelines can be sustained. This trend is an artifice that traces to the focus of this paper on the practical range of hydrotesting conditions. Accordingly, failure mechanisms beyond that controlling hydrotest behavior have not been embedded in the equations presented in Leis and Rahman (1994). Had these mechanisms (e.g., significant yielding) been included, the transition from failure associated with removing cracks by the creep mechanism at typical hydrotest pressures to a time-independent yielding at the higher pressures would tend to zero at much lower pressures.

The time-evolution of failure probability for the test pressure of p = 1430 psi is also shown in Fig. 11. All these results are obtained by direct MCS. Note from this figure that the probability of failure levels off within a few hundred seconds for this particular case. However, the probability of failure continues to increase, although at very much lower rates through the full duration of the hold time. This result indicates that most cracks will grow through the wall very early in the hold time, which in turn suggests that long hold times are not particularly beneficial. These results also suggest that the high pressure imposed on the line to remove near-critical cracks could be reduced to a lower level for the purpose of the leak check.

Analysis like that in Fig. 11 indicates the possibility of cracks failing throughout a hydrotest. Data such as this would permit quantitative estimates of the chance for stress reversals due to stopping hydrotests after the failure rate diminishes. Similarly, plots like this would permit study of different hydrotest histories to tailor the test parameters to each line. Such analysis could form the basis for test strategies designed to maximize the benefits of a hydrotest, particularly in dealing with lines that have a history of multiple failures and stress reversals.

6 Summary and Conclusions

This paper explored the significance of the random nature of the variables related to serviceability in pipelines subjected to flaw growth in service. This study was made under the assumption that continuing serviceability is based on the use of hydrotesting. Results generated via probabilistic analysis with the theoretical models presented in Leis and Rahman (1994) formed the basis for the discussion of risk and safety and the significance of the random variables.

A numerical example was presented in light of a hydrotest-based approach to ensure pipeline integrity. A pipe with random crack geometry and random material properties was analyzed to determine probabilistic characteristics of several response variables of interest. The proposed probabilistic model predicted accurately the crack-growth characteristics when compared with observed hydrotest data, including the size of the flaws removed from the crack size population by the test. Statistical properties of failure pressure were determined and failure probability was predicted for a given hydrotest pressure, which also compared very well with actual test data. Quantitative correlation with traditional safety factor was developed.

Effects of time-dependent creep deformation were also investigated. The time-evolution of failure probability was seen to level off within a few hundred seconds. The probability of failure was predicted to continue to increase, although at very much lower rates through the full duration of the hold time, which indicates that most cracks will grow through the wall very early in the hold time. These results indicate that long hold times are not particularly beneficial and that the pressure in the line designed to remove cracks could be reduced to a lower level for the purpose of the leak check. Quantiative estimates of the chance for stress reversals due to flaw growth in a prior hydrotest were noted as an option within the framework of the analysis presented. Similarly, analysis of different hydrotest histories to tailor the test parameters to each line were noted as the basis to design strategies that maximize the benefits of a hydrotest, particularly in dealing with lines that have a history of multiple failures and stress reversals.

A number of conclusions can be drawn based on the results of this paper. Of these, the most important is that analysis of hydrotest strategies to optimize safety for such populations, e.g., "Hydrotest Strategies for Gas Transmission Pipelines," would be enhanced greatly by a probabilistic analysis that permits risk assessments associated with the type and frequency of hydrotests done to ensure continued safe operation of the line. The merits of developing a probabilistic framework for the analysis of pipeline integrity carry well beyond designing hydrotests to ensure integrity. This same probabilistic framework could be used in risk and safety assessments associated with pipeline operating decisions during in-line inspection.

References

Brust, F. W., and Leis, B., 1992, "A New Model for Characterizing Primary Creep Damage," *International Journal of Fracture*, Vol. 54, pp. 45-63.

Brust, F. W., and Leis, B. N., 1990, "A Study of Primary Creep Crack Growth at Room Temperatures," *Proceedings of the 5th International Conference on Numerical Methods in Fracture Mechanics*, eds., A. R., Luxmoore and D. R. J. Owen, Freiburg, Germany, Apr., pp. 321-332.

Brust, F. W., and Leis, B. N., 1990, "The Effects of Primary Creep on Elastic-Plastic Crack Growth," *Fatigue, Degradation, and Fracture*, ASME PVP-Vol. 195; also, see MPC-Vol. 30.

Kiefner, J. F., Maxey, W. A., Eiber, R. J., and Duffy, A. R., 1973, "Failure Stress Levels of Flaws in Pressurized Cylinders," ASTM STP 536, pp. 461-481.

Leis, B. N., and Rahman, S., 1994, "Risk-Based Considerations in Developing Strategies to Ensure Pipeline Integrity—Part I: Theory, " ASME JOURNAL OF PRESSURE VESSEL TECHNOLOGY, Vol. 116, Aug., pp. 278-283.

Leis, B. N., and Rahman, S., 1993, "Risk-Based Considerations in Developing Optimum Hydrotest Strategies," *Proceedings of Gas Technology Symposium*, Society of Petroleum Engineers, Calgary, Alberta, Canada, June.

Leis, B. N., and Brust, F. W., 1992, "Hydrotest Strategies for Gas Transmission Pipelines Based on Ductile-Flaw-Growth Considerations," NG-18 Report No. 194, American Gas Association Catalog No. L51665, July.

Leis, B. N., Brust, F. W., and Scott, P. M., 1991, "Development and Validation of a Ductile Flaw Growth Analysis for Gas Transmission Line Pipe," Report to the American Gas Association (AGA), NG-18 Report No. 193, June.