A Predictive Model for Optimizing Hydrostatic Test Pressures in Seam-Welded Pipelines

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ABSTRACT. There is broad consensus that hydrostatic testing is a valuable integrity management tool for seam-welded pipelines, but there are varying opinions over specific hydrotesting procedures, including the most appropriate test pressures. This paper presents a modeling framework that optimizes hydrostatic test conditions in terms of both integrity and economic value. Increasing the hydrostatic test pressure tends to increase the calculated fatigue life in sections that pass the test, but there are deleterious effects of excessive test pressures. For example, a hydrostatic test is impractical if it results in failure of a significant fraction of pipe joints in the line. Predictive modeling of hydrostatic testing, based on the best available technology, is offered as a rational means to select test conditions that maximize the benefits and minimize the negative impact on a given pipeline. The predictive modeling framework is demonstrated with several examples.

There is no one-size-fits-all test pressure (relative to SMYS) that is appropriate for all situations. The optimum test pressure for a given pipeline is governed by a variety of factors, including vintage, operating conditions and prior integrity management actions (e.g. hydrotesting and ILI).

OVERVIEW

Hydrostatic testing continues to play an important role in the integrity management of seam-welded pipe. A key question in any hydrostatic test is: what is the most appropriate maximum test pressure? There are varying opinions on the matter among operators, regulators, service providers, and consultants. This paper makes the case that the maximum test pressure should be chosen based on the best available science and technology rather than subjective opinions.

A predictive modeling framework that optimizes test pressures is presented below. This model incorporates state-of-the-art fracture mechanics methodology, as well as data on material properties and flaw populations that has been inferred from prior in-service and pressure test failures.

Increasing the hydrostatic test pressure tends to increase the calculated fatigue life in sections that pass the test. On the other hand, there are deleterious effects of excessive test pressures. For example, a hydrostatic test is impractical if it results in the failure of a significant fraction of pipe joints in the line. If a vintage pipeline with poor toughness and significant flaws is subject to a sufficiently high test pressure, the cost of remediating a large number of failures may approach the replacement cost of the pipeline. The predictive model is a tool for determining a test pressure that optimizes the value derived from a hydrostatic test.

MODELING FRAMEWORK

Figure 1 illustrates how hydrostatic testing is typically used to ensure integrity of pipelines subject to in-service flaw growth. Referring to the sketch on the left, the red curve corresponds to the critical flaw dimensions at the hydrotest pressure, which are computed from a fracture model. Flaws above the red curve are assumed to be eliminated by the test. The blue curve represents the critical flaw dimensions at the maximum operating pressure (MOP). A remaining life calculation can be performed to estimate the time required for a flaw on the red curve to grow to the blue curve. In the case of a seam-welded pipeline that experiences pressure cycling, a pressure cycle fatigue analysis (PCFA) is usually used to estimate the remaining life following a hydrostatic test.

The sketch on the right side of Fig. 1 illustrates the effect of test pressure on remaining life estimates. As test pressure increases for a given MOP, the distance between the red and blue curves increases. In other words, the starting flaw size for a fatigue analysis decreases with increasing test pressure, which results in a longer calculated remaining life.

Based solely on conventional PCFA models, the benefits of hydrostatic tests appear to increase with test pressure indefinitely. Reality is more complex, however. Excessively high test pressures can damage the pipeline. An inordinate number of ruptures during a hydrostatic test can have an unacceptable economic impact. Pipe joints with strength properties at the lower tail of the bell curve may experience diameter swelling, which results in higher hoop stresses in subsequent operation. Moreover, conventional PCFA models do not account for fatigue retardation following a hydrotest, which prolongs life. The beneficial effects of fatigue retardation can be greater at moderate test pressures, so the true life of a pipeline does not necessarily increase monotonically with test pressure.
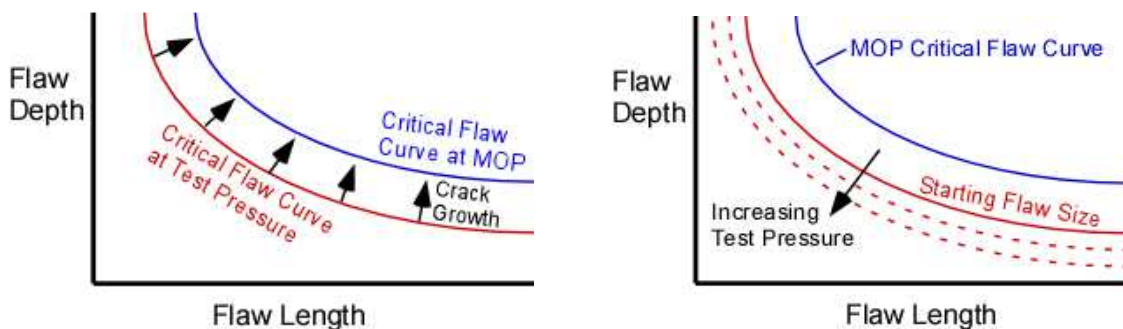
FIGURE 1. Integrity management with hydrostatic testing of a pipeline that experiences in-service flaw growth.

The modeling framework proposed herein takes account of a variety of factors that influence the outcome of a hydrostatic test. The key ingredients of this framework are as follows:

1. PRCI MAT-8 fracture model [1].
2. Probabilistic PCFA model [2].
3. Fatigue retardation model [3].
4. Probabilistic fracture model to forecast hydrotest failures.
5. Benchmarking and calibration of models to real-world data and experience.

These five ingredients are discussed below.

The PRCI MAT-8 fracture model [1] consists of curve fits to 3D elastic-plastic finite element analyses. An accurate state-of-the-art fracture model is a foundational component of the hydrotest modeling framework. Traditional pipeline fracture models such as Log-Secant suffer from a number of serious shortcomings and are incapable of accurate burst predictions [4].

Even with the most accurate analytical models for fatigue and fracture, there are significant uncertainties in the input parameters, which of course translates to uncertainties in output. Material properties, for example, can vary significantly between joints and at multiple microstructures (e.g. pipe body, bond line and heat-affected zone in ERW pipe) within a joint. Moreover the size and location of seam weld flaws is essentially random. Even when flaws have been characterized with inline inspection (ILI), there is a high degree of flaw sizing error and uncertainty. Consequently, it is appropriate to view remaining life probabilistically rather than deterministically. A probabilistic PCFA algorithm has recently been developed [2] that takes account of the inherent uncertainties in material properties, flaw population and other key inputs. The output of a probabilistic PCFA is a plot of probability versus remaining life, as Fig. 2 illustrates. The probability curve typically shifts to the right with increasing test pressure, but diminishing returns or a reverse trend may be observed at high pressures.
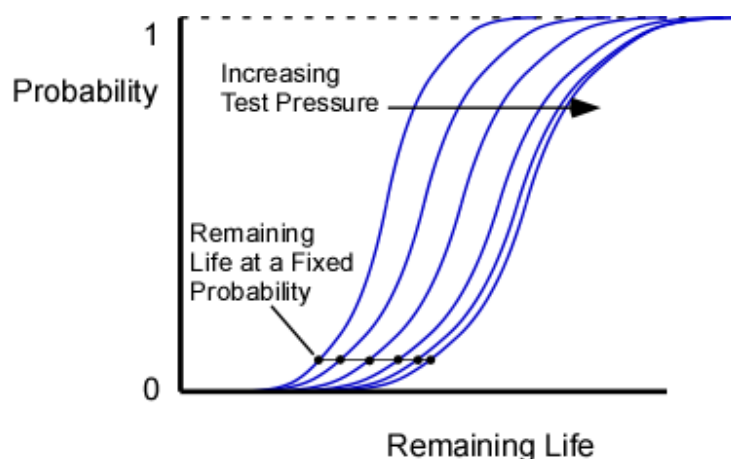

FIGURE 2. Probabilistic pressure cycle fatigue analysis.

Traditional PCFA models do not account for the effect that the hydrostatic test has on the subsequent crack growth rate. Figure 3 illustrates the crack closure mechanism for fatigue retardation following an overload event such as a pressure test. The load spike produces a large plastic zone at the crack tip. When the load is removed, compressive residual stresses form in the overload zone. When the crack propagates into the overload zone, the compressive residual stresses hold the crack closed during a portion of some loading cycles, which results in a diminished crack growth rate. As the sketch on the right side of Fig. 3 indicates, fatigue retardation following a pressure test results in an extension in life relative to what would have been observed in the absence of the test.

A recent study [3] sought to quantify the effect of hydrostatic testing on subsequent crack growth. This study consisted primarily of 3D elastic-plastic finite element simulation of pressure cycling and crack propagation. These analyses resulted in predictions of crack closure following a pressure test, which can be used to quantify the resulting fatigue crack growth behavior.

While increases in hydrostatic test pressure *tend* to increase the calculated remaining life, the offsetting negative consequences of higher test pressures must also be considered. For example, there will be a greater incidence of failures at higher test pressures, because more flaws in the overall population will be above the critical size as pressure increases. The burst pressures of the various joints in a pipeline follow a statistical distribution, as Fig. 4 illustrates. The red shaded area on the left diagram represents the subset of the population of pipe joints where the burst pressure is ≤ the test pressure. Of course, the number of joints that fail is directly related to the test pressure. The diagram on the right side of Fig. 4 indicates that the burst pressure distribution is specific to a particular pipeline. A vintage pipeline may have larger and more numerous seam weld flaws than a modern pipeline, and the toughness properties of the vintage line may be inferior compared to the modern pipeline.

Given that a large number of ruptures in a hydrostatic test may have significant consequences economically and otherwise, a forecast of the expected number of failures as a function of test pressure would be useful in the decision-making process. An example of such a forecast is presented later in this paper.
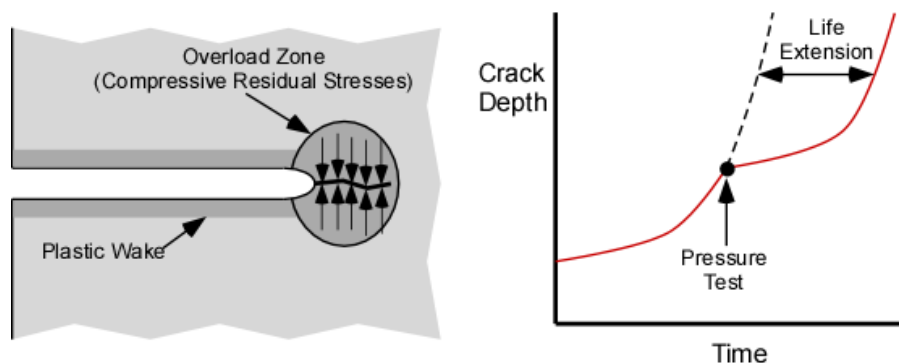

FIGURE 3. Crack closure mechanism for fatigue retardation following a pressure test. The overload generates a zone of compressive residual stresses at the crack tip, which results in slower fatigue crack propagation due to crack closure.

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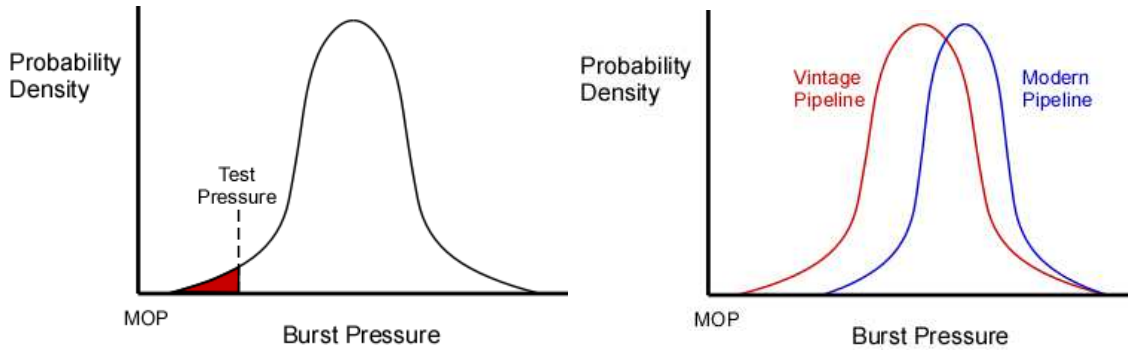
FIGURE 4. Statistical distribution of burst pressures of pipe joints. The red shaded region represents the number of failures at a given test pressure. The burst pressure distribution is unique to a given pipeline.

Comparing the trade-offs of beneficial and detrimental impacts of hydrostatic testing can lead to a rational decision on the optimum test pressure in a given situation. Figure 5 illustrates a hypothetical scenario where the calculated remaining life (blue curve) increases monotonically with test pressure, but with diminishing returns at high pressures. The red curve represents the forecast number of failures. If the test pressure is too low, the calculated remaining life is short, which means that hydrostatic testing would need to be repeated frequently. If the test pressure is too high, remediation costs from ruptures may be prohibitive. The optimum test pressure range in this case corresponds to a relative high remaining life and a manageable number of hydrotest failures.

Figure 5 is a qualitative visual representation of the optimum hydro test conditions. A more quantitative and objective decision process is possible. For example, a financial model could be used to minimize the annualized cost of pressure testing. Given a fixed cost of pressure testing, the annualized cost decreases in proportion to the allowable number of years of operation until the next test. All else being equal, prolonging the estimated remaining life is beneficial financially. At high test pressures, however, the total cost of pressure testing could increase significantly if there are an inordinate number of failures.
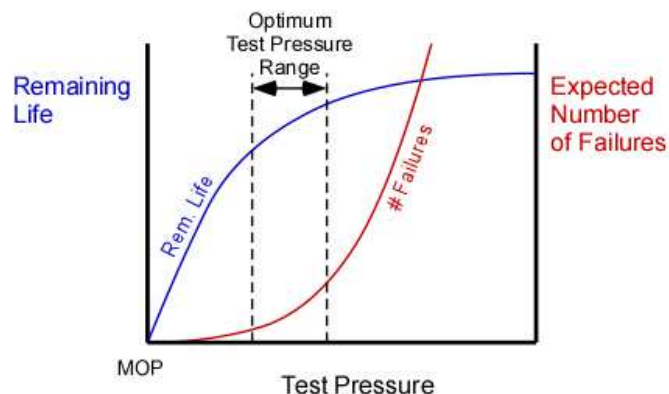
FIGURE 5. Determining optimum hydrostatic test conditions based on a comparison of positive and negative impacts.

Mathematical models can be simple or highly complex, but even the most sophisticated models are idealized representations of reality. In the case of seam-welded pipe, there are a number of key differences between the real world and the models that attempt to represent this reality. For example, fracture mechanics models assume sharp planar cracks with regular (e.g. semi-elliptical) profiles, while seam weld flaws seldom conform to this ideal. Hook cracks are usually not planar and lack-of-fusion flaws typically have a blunt tip radius. Many real-world flaws have an irregular profile. In theory, it is possible to develop failure models for realistic flaws, but such an endeavor is impractical. Since no two flaws are alike, it would be an insurmountable challenge to create failure models for every possible scenario. A more fundamental difficulty is that the precise characteristics of individual seam weld flaws in a given pipeline are simply unknowable without destructive testing of every pipe joint.

The situation is not hopeless, however. Mathematical models have value as predictive tools if they are benchmarked and calibrated to real-world observations. For example, a fracture mechanics model that assumes ideal planar cracks can be a proxy for actual seam weld flaws if it is properly calibrated to pipeline failures that occur in service or during pressure testing. The bottom line is that models can predict the future if they are calibrated to the past.

APPLICATIONS OF THE MODELING FRAMEWORK

The analyses that follow were performed on an actual 16-inch high-frequency ERW pipeline. The wall thickness is 0.25 inch and the material is API 5L-X52. The line transports crude oil and is approximately 250 miles in length. The maximum allowable operating pressure (MAOP) is 1170 psi, which corresponds to 72% specified minimum yield strength (SMYS).

Effect of Fatigue Retardation

A series of pressure cycle fatigue analyses were performed to demonstrate the relative effect of fatigue retardation, based on modeling results from Ref. [3]. The analyses were deterministic in this case because we have yet to incorporate retardation effects into the probabilistic PCFA module.

The results of the fatigue analyses are plotted in Figs. 6 to 8. Figure 6 shows results pertaining to pressure cycling at a pumping station discharge, designated as Station X for the purpose of identification in this paper. The retardation model has little impact on the predicted lives because there are few low-pressure excursions at the discharge to Station X. Fatigue retardation is the result of crack closure, which occurs only when pressure drops to low values. Figure 7, which corresponds to the suction of the pumping station downstream of Station X, shows a more significant impact of fatigue retardation. In this case, there are more frequent low-pressure excursions. Note that the life versus hydrostatic test pressure curve that includes retardation is flatter than the other curve because retardation effect are more pronounced below 100% SMYS.
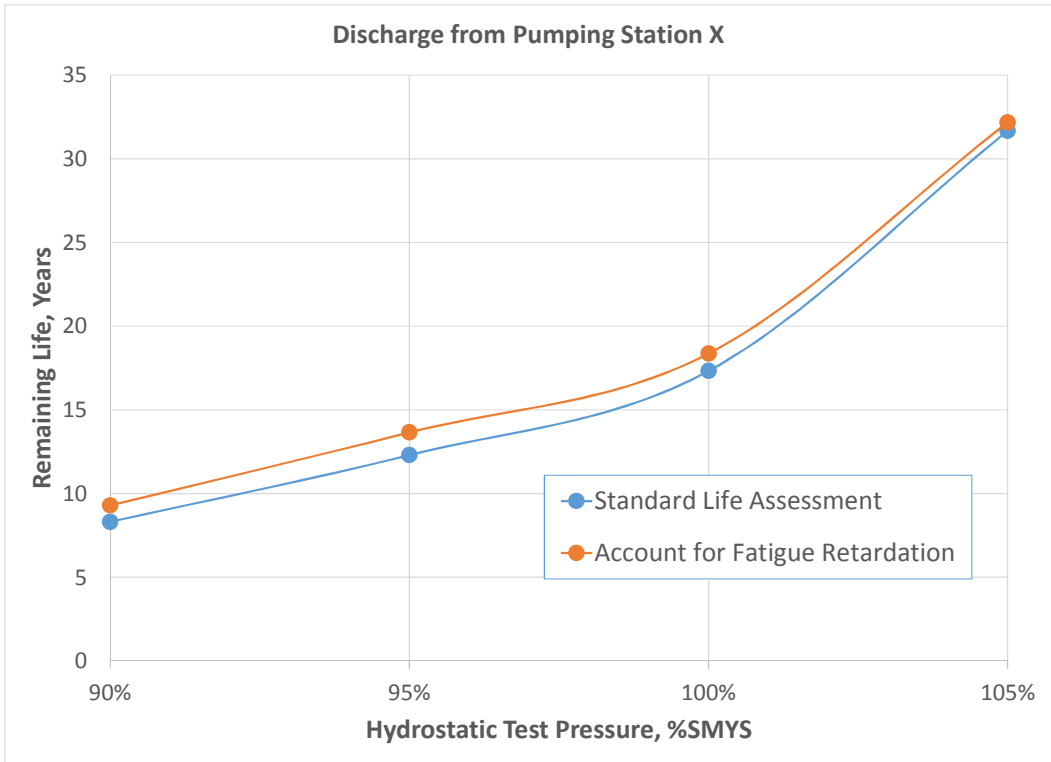
FIGURE 6. Effect of hydrostatic test pressure and fatigue retardation on remaining life at a pumping station discharge.
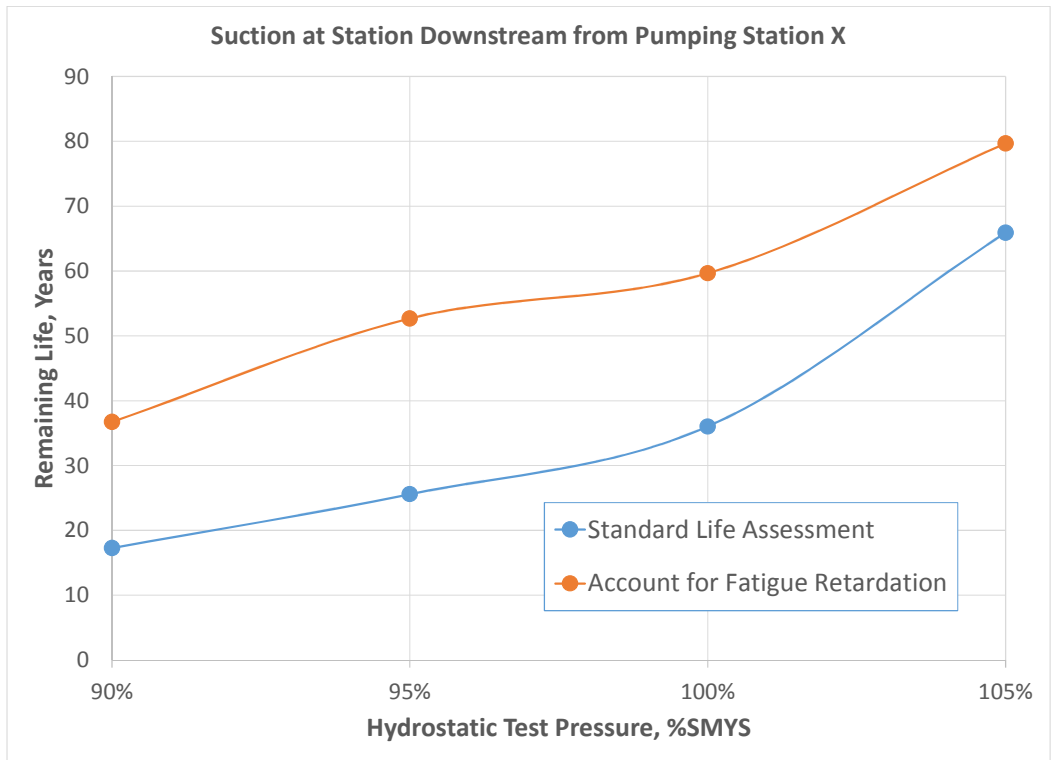
FIGURE 7. Same as Fig. 6, but at the suction of the pumping station downstream from Station X.

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Figure 8 corresponds to a hypothetical pressure history that was obtained by capping the suction pressure data (Fig. 7) at 50% SMYS. The unaltered pressure data for the pumping station suction location actually showed that pressure seldom exceeded 50% SMYS, so capping the pressure had little effect on cyclic loading. However, reducing MOP from 72% to 50% SMYS prolongs the life for two reasons:

1. The critical flaw size increases when MOP decreases. Referring to Fig. 1, the blue curve shifts upward and to the right with decreasing MOP.
2. The magnitude of crack closure and the resulting retardation are a function of the ratio of the test pressure to MOP [3]. Decreasing MOP results in greater retardation in crack growth, given the same test pressure.

The upper curve in Fig. 8 indicates that fatigue life actually *decreases* when test pressure exceeds 95% SMYS because fatigue retardation effects, which exhibit a decreasing trend with test pressure (see below), overwhelms other factors. Consequently, there is little or no value in higher test pressures in this case, particularly since remediation costs will increase with test pressure due to hydrotest failures.

Figure 9 is a plot of the ratio of calculated fatigue lives with and without retardation effects incorporated into the analysis. The relative impact of retardation decreases with test pressure in all cases considered. This trend can be explained by in terms of the mechanism for formation of compressive residual stresses at the crack tip following a pressure test. The highest residual stresses are generated when the plastic zone created during the hydrotest is contained within material that is stressed in the elastic range. When the test pressure is removed, the elastically deformed material recovers its original shape, which compresses the overload zone. When the entire ligament in front of the crack deforms plastically, the relative magnitude of the compressive forces exerted on the overload zone is less.

Finally, one should not focus on the *absolute* magnitude of the fatigue lives shown in Figs. 6 to 8. These life calculations were based on a deterministic model with a particular set of assumptions on material properties and crack aspect ratios. The purpose of Figs. 6 to 8 is to demonstrate the *relative* impact of test pressure, with and without fatigue retardation effects taken into account.
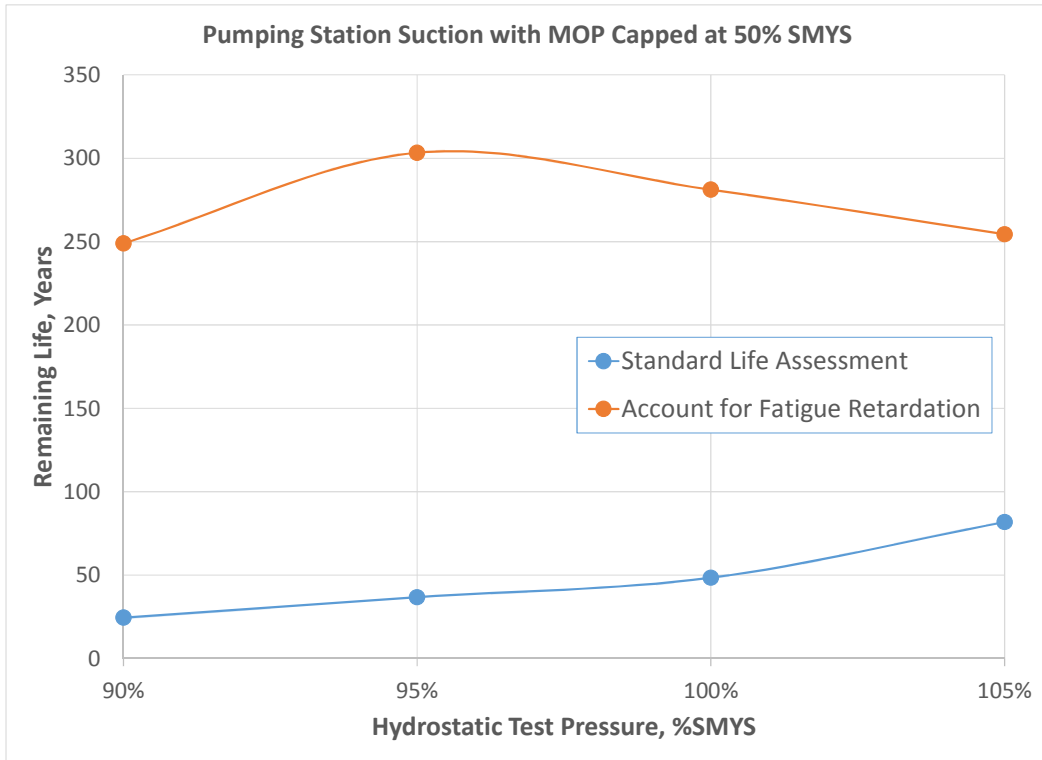
FIGURE 8. Same as Fig. 7, but with MOP capped at 50% SMYS.
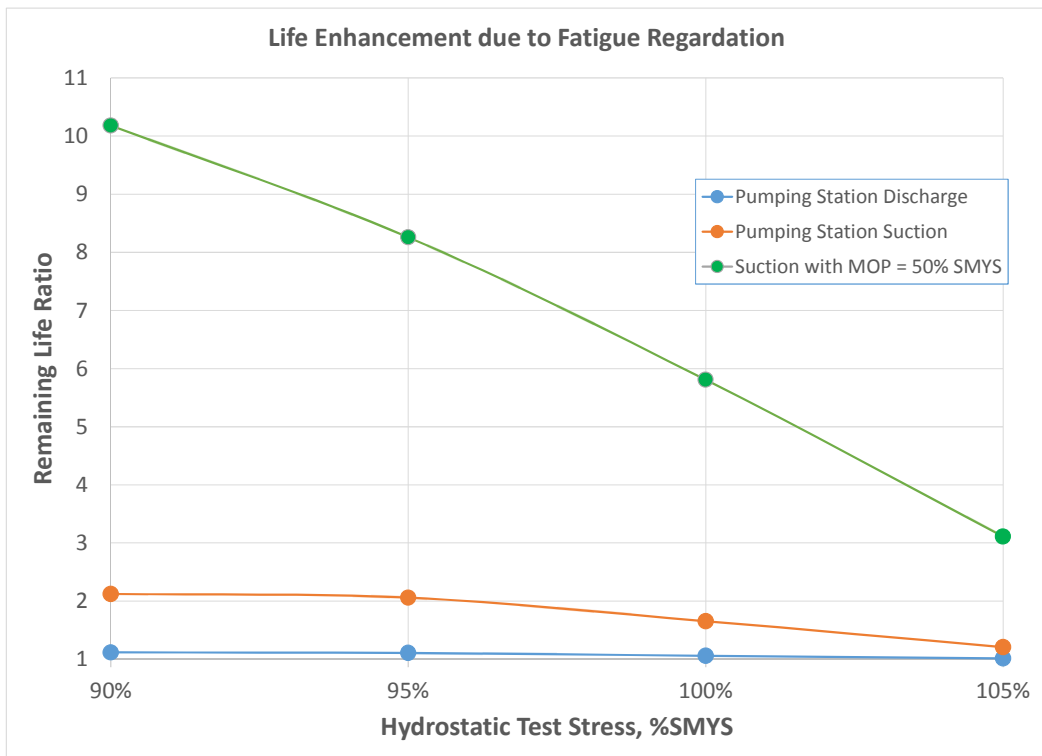
FIGURE 9. Ratio of life estimates with and without including retardation effects.
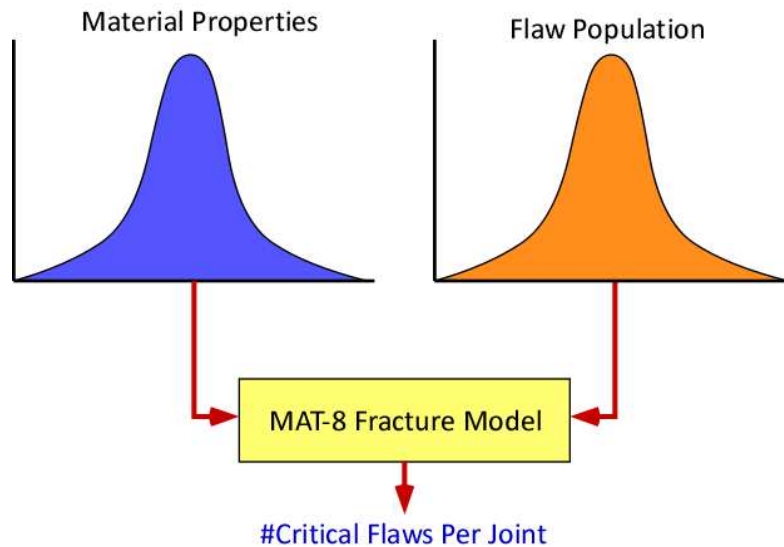
Forecasting Hydrotest Failures

A probabilistic fracture analysis can be used as a tool to forecast the number of expected failures. The process is illustrated in Fig. 10. The key material properties are strength and toughness. This model accounts for the variability in material properties between joints. The flaw population is influenced by prior operation and integrity actions. For example, if the pipeline has been subject to a hydrostatic test within the past 5 years, there will be a cap on the largest flaws that can be present. On the other hand, if a 60-year-old line has never been tested during its lifetime, there is a high likelihood that large flaws are present. Data from an ILI crack tool run can also inform the choice of the flaw population.

The output of the probabilistic model is an estimate of the average number of critical flaws per joint at a given test pressure. The *expected value* for total hydrotest failures is simply the critical flaws per joint times the number of joints tested. This does not mean that the actual outcome will line up perfectly with the expected value. The Poisson distribution can be used to estimate the likelihood of various outcomes. The probability that the number of failures, *M*, will equal a particular value, *m*, is given by

$$P_{(M=m)} = \frac{(\rho N)^m}{m!} e^{-\rho N} \qquad m = 0,1,2\ldots \tag{1}$$

Where ρ is the average critical flaws per joint and *N* is the number of joints tested.

Figure 11 shows the flaw population data used for the present example. These data were inferred from a shear wave ILI crack tool run, which identified 1,050 crack-like flaws in approximately 250 miles. Note the distinction between the *total* flaw population versus the population of *critical* flaws. The latter is a much smaller population and is a function of test pressure. The total flaw population is an input to the probabilistic fracture model, which outputs the critical flaw population, as Fig. 10 illustrates. The flaws detected by ILI were ranked in order of severity, as defined by the modified B31G remaining strength equation. Note that although the remaining strength factor (RSF) was used for ranking purposes, the PRCI MAT-8 fracture model was used for burst calculations.

FIGURE 10. Probabilistic fracture analysis for forecasting the number of failures in a hydrotest.

Table 1 lists the estimated critical flaws per joint and the expected number of failures for a range of test pressures. The third column in Table 1 lists the average number of joints that must be sampled to find one critical flaw. This value is the reciprocal of the critical flaws per joint.

Figure 12 is a plot of expected failures versus test pressure. As stated earlier, the actual outcome will not necessarily match the expected values. Figure 13 shows the probability of each outcome, as computed from the Poisson distribution (Eq. (1)). The corresponding cumulative probability of the various outcomes is plotted in Fig. 14.
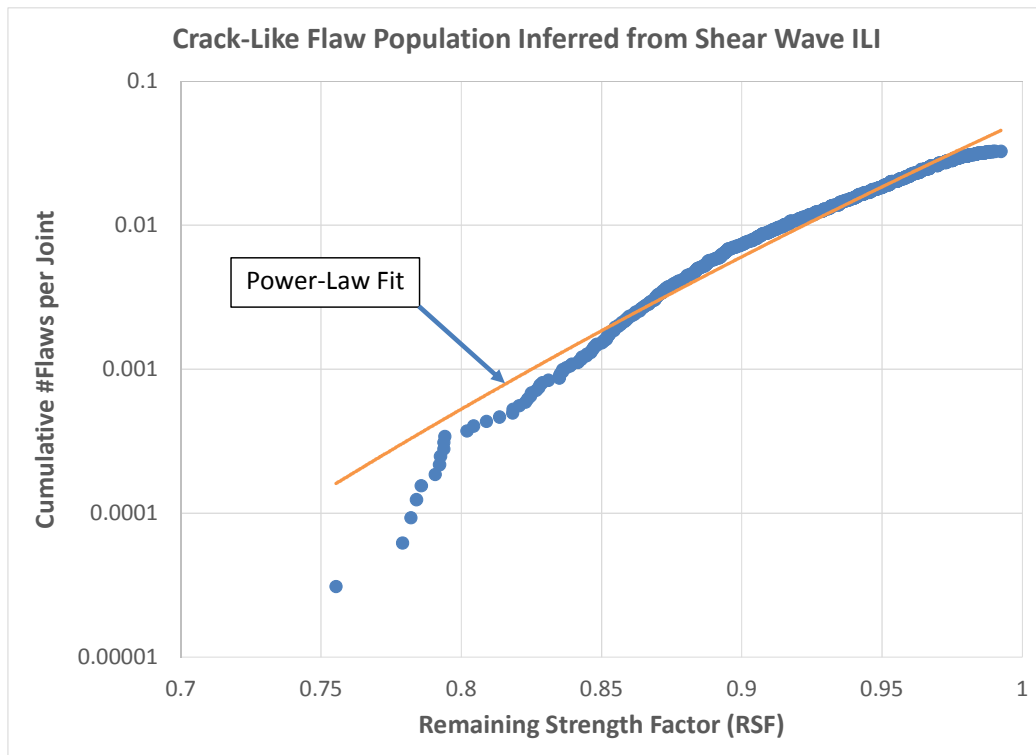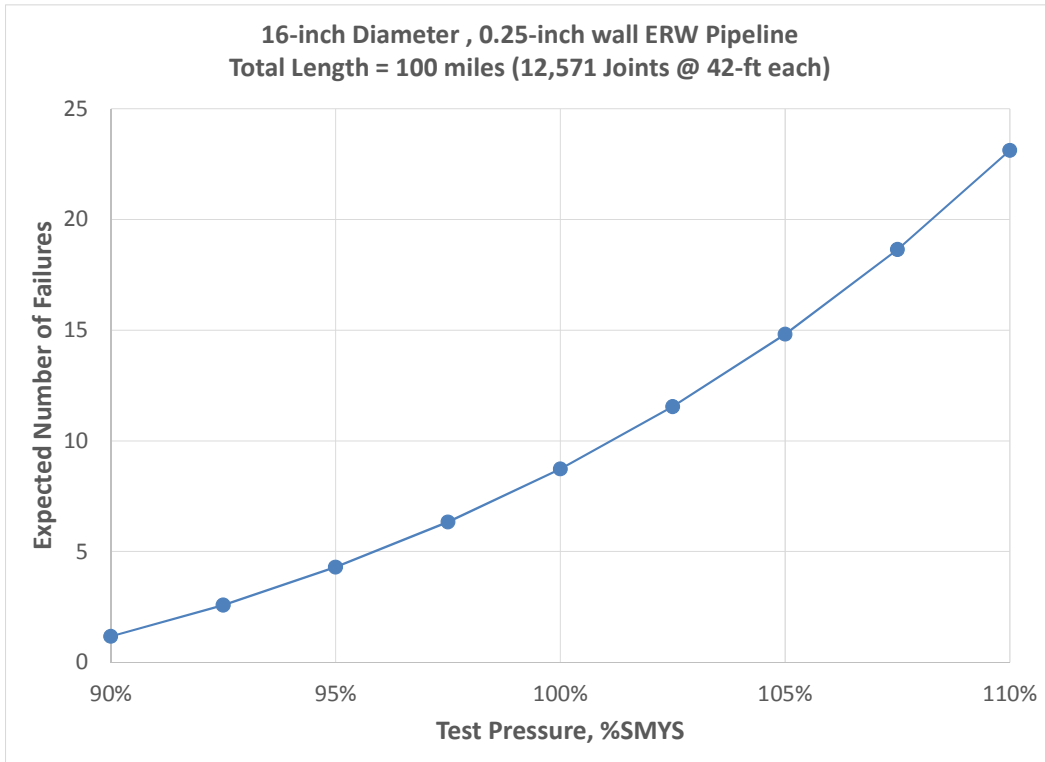

**FIGURE 11.** Example flaw population from an ILI shear wave UT tool run.

TABLE 1.

Results of the probabilistic fracture analysis example.

Test Pressure	Avg. Critical Flaws per Joint	Avg. Joints per Critical Flaw	Expected Failures in 100 miles (12,751 Joints)
90% SMYS	9.24×10^{-5}	10,819	1
95% SMYS	3.41×10^{-4}	2,926	4
100% SMYS	6.95×10^{-4}	1,439	9
110% SMYS	1.18×10^{-3}	848	15

FIGURE 12. Expected hydrotest failures as a function of test pressure.
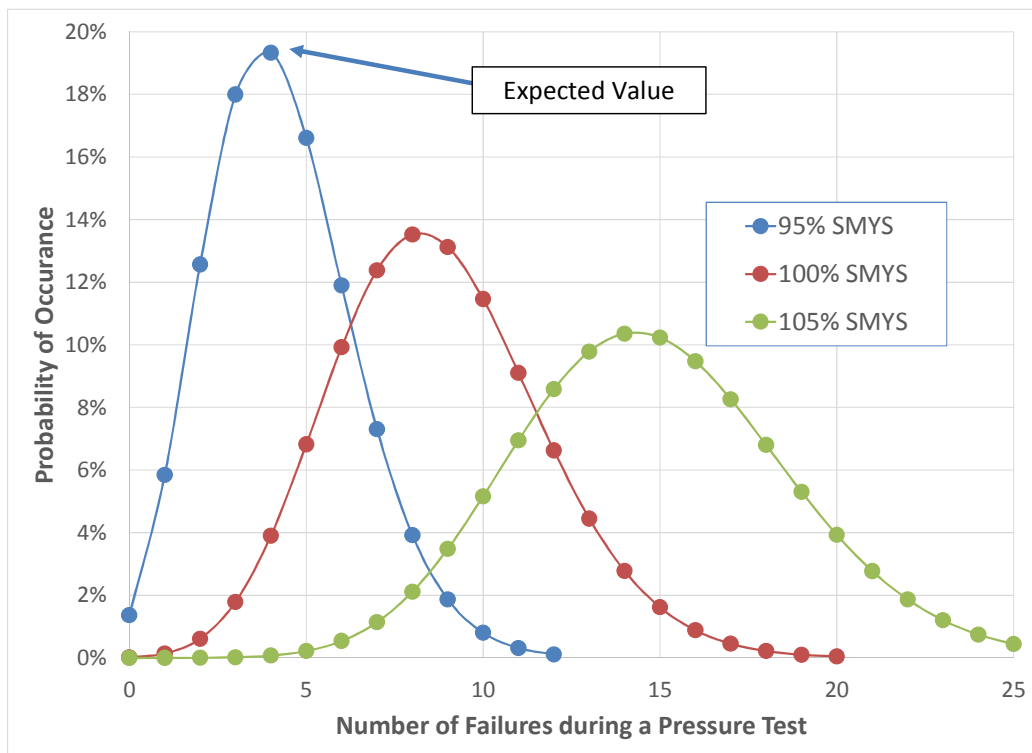
FIGURE 13. Variability in hydrotest failures, inferred from the Poisson distribution.
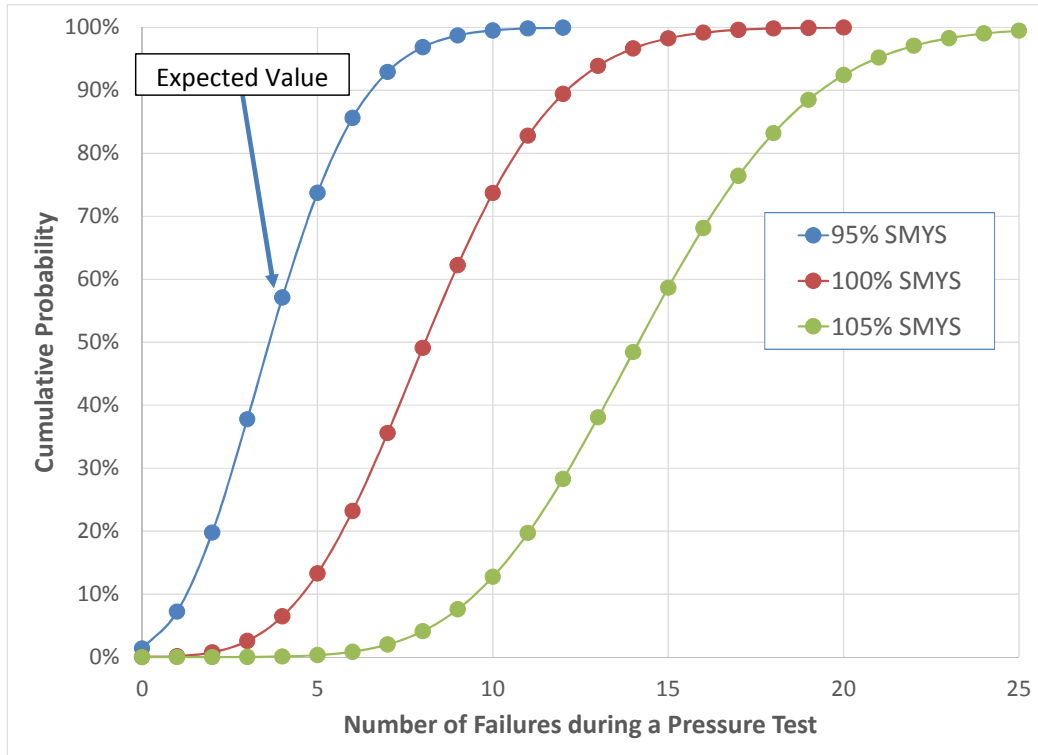
FIGURE 14. Data from Fig. 13, plotted in terms of cumulative probability.

CONCLUDING REMARKS

The forgoing examples are demonstrations of what is possible with state-of-the-art fracture mechanics models, combined with probability and statistics. Further work is necessary to calibrate and benchmark this modeling framework to real-world experience. A data mining exercise is currently underway to extract relevant information on prior failures and inspection results from both published and unpublished sources.

One conclusion is clear from the work completed to date. There is no one-size-fits-all test pressure that is appropriate for all situations. Advocating a universal test pressure (e.g. 105% SMYS) is counterproductive to pipeline integrity. Optimizing hydrostatic test conditions for each unique situation in terms of both integrity and economic value is arguably a superior strategy to adopting inflexible rules.

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