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Innovations in the Integrity Management of Seam Welds in Cyclic Service

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ABSTRACT. Pipelines with seam welds that are in cyclic service can suffer fatigue damage that can lead to failures. Pressure cycle fatigue analysis (PCFA) is performed to predict the remaining life of seam flaws, and forms the basis for decision making on these pipelines. This paper will describe several innovations that have been developed to continue to improve the PCFA process. These innovations include:

- A *Cyclic Index*, which provides a quantitative measure of the severity of pressure cycling. The Cyclic Index can be viewed as a "pressure cycle speedometer".
- A probabilistic PCFA model for remaining life estimates in pipelines subject to pressure cycling. The probabilistic model accounts for uncertainties in input parameters and improves predictions of the effect of ILI and hydrotest results on the flaw sizes that remain in the pipeline after integrity management activities.
- The application of new assessments to seam weld integrity management including use of the *Cyclic Index* and an approach to evaluate the relative effectiveness of hydrotest and in-line inspections.
- The Pacifca™ integrity management software platform for pipelines subject to pressure cycling. This software can be integrated with pipeline SCADA systems to automatically gather pressure data for multiple pipelines and process these data through PCFA computations.

OVERVIEW OF PRESSURE CYCLE FATIGUE ANALYSIS (PCFA)

Pipelines that are subject to pressure cycling (i.e. the pressure fluctuates rather than remaining steady) can develop fatigue cracks in service. Pressure cycling is primarily a problem in liquid lines, but fatigue failures have occurred in gas lines. Fatigue cracks typically initiate at pre-existing weld flaws, so ERW pipe with hook cracks and lack of fusion flaws is particularly susceptible.

Pressure cycle fatigue analysis (PCFA) is an important part of integrity management of pipelines in cyclic service. Figure 1 illustrates the typical PCFA methodology. Pressure versus time data at a given location in the pipeline are processed through a rainflow cycle counting algorithm, resulting in a cyclic pressure histogram. Next, an initial flaw size is determined based on hydrostatic test results, inline inspection (ILI), or a combination of both. The specified initial flaw dimensions, along with pipe dimensions and material properties, are fed into a fracture mechanics model that predicts the remaining life of the pipe joint that contains the flaw. A factor of 2 is typically applied to the calculated life to establish the recommended time to the next hydrotest or ILI tool run.

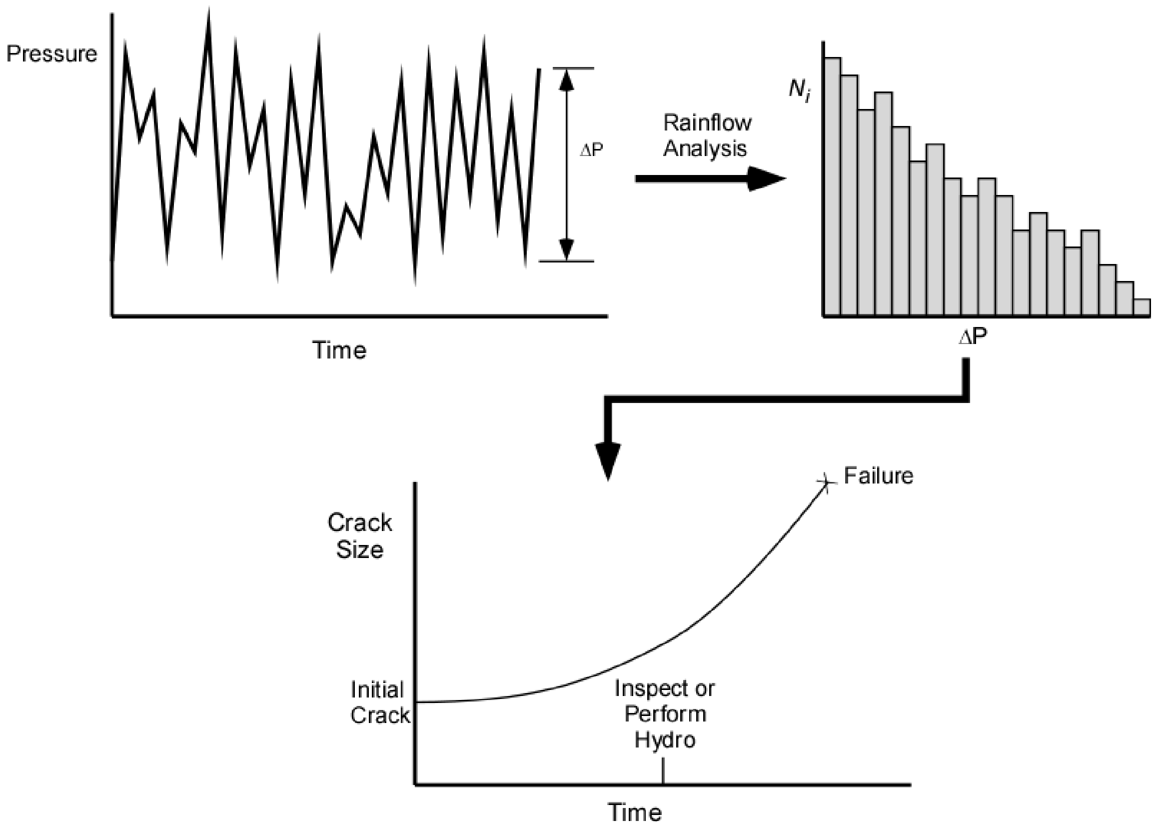

FIGURE 1. Pressure cycle fatigue analysis (PCFA). Pressure versus time data are processed through a rainflow cycle counting algorithm to produce a cyclic pressure histogram. This information is then used to predict the growth of a pre-existing crack.

The rate of fatigue crack growth per pressure cycle, da/dN, is usually inferred from the Paris equation:

$$\frac{da}{dN} = \begin{cases} C\left(\Delta K\right)^m & \Delta K > \Delta K_{th} \\ 0 & \Delta K \le \Delta K_{th} \end{cases} \tag{1}$$

Where ΔK is the cyclic stress intensity factor [1], C and m are material constants, and ΔK_{th} is the threshold value of ΔK, below which fatigue crack growth does not occur.

Given a cyclic pressure histogram, the crack growth rate must be computed for each histogram bin. The average crack growth rate in terms of time (e.g. inches per year) is inferred by summing over the histogram:

$$\frac{da}{dt} = \frac{\sum \left(\frac{da}{dN}\right)_i N_i}{\Delta t} \tag{2}$$

where Δt is the time interval over which the histogram was collected, $(da/dN)_i$ is the crack growth rate for the ith histogram bin, and N_i is the number of cycles in the ith bin. The time to failure, t_f, is obtained by integrating the crack growth rate from the initial flaw size, a_o, to the critical flaw size at failure, a_f:

$$t_f = \int_{a_o}^{a_f} \frac{da}{(da/dt)} \tag{3}$$

The critical flaw size is computed from a failure model, such as the API 579 failure assessment diagram (FAD) method [2] or the PRCI MAT-8 method [3].

While PCFA can provide useful information, and is an essential part of an effective integrity management plan for pipelines subject to pressure cycling, there are a number of shortcomings with traditional methods. For example, there is often a high degree uncertainty in the inputs to the analysis, such as flaw dimensions and material properties. Also, PCFA can be time consuming when performed with traditional tools. The sections that follow describe several recent innovations in integrity management of pipelines that experience pressure cycling.

DEVELOPMENT OF A CYCLIC INDEX

The severity of pressure cycling can vary significantly between pipelines. Moreover, there can be large variations in pressure cycle severity in a given line at various locations, or at different times at the same location. Consequently, it is important to have an objective method to quantify pressure cycle severity in order to assess the threat level.

In the past decade, the pipeline industry in North America has adopted a subjective categorization of pressure cycle severity, which is described in the TT05 document [4]. A given cyclic pressure histogram is evaluated and assigned one of four categories: Light, Moderate, Aggressive and Very Aggressive. Table 1 lists the benchmark cycle counts for each of these categories.

TABLE 1.
TT05 benchmark annual cycle counts for the four categories [4].

Percent SMYS	Very Aggressive	Aggressive	Moderate	Light
72%	20	4	1	0
65%	40	8	2	0
55%	100	25	10	0
45%	500	125	50	25
35%	1000	250	100	50
25%	2000	500	200	100
Total	**3660**	**912**	**363**	**175**

Aside from being subjective, the TTO5 categories suffer from another major shortcoming. Namely, the cyclic hoop stress in Table 1 is expressed as a percentage of specified minimum yield strength (SMYS). The Paris constants (*C* and *m*), which characterize fatigue crack growth, are not sensitive to strength properties. Consequently, an Aggressive rating in a pipeline made from a high strength steel grade (e.g. API 5L X80) represents far more severe cycling than an Aggressive rating in a low strength pipe (e.g. X42). Given the same rating, an X80 pipe will have a much shorter remaining life than an X42 pipe.

Quest Integrity has recently developed a quantitative cyclic index as an alternative to the TTO5 pressure cycle categories. This index is a number that is proportional to the fatigue damage rate. Given a histogram of cyclic hoop stress values, $\Delta\sigma_i$, an equivalent number of cycles per year at a constant stress amplitude can be computed as follows:

$$N_{eq} = \frac{\sum \Delta\sigma_i^{\ m} N_i}{\Delta\sigma_{eq}^{\ m}} \left(\frac{1 \text{ year}}{\Delta t} \right) \tag{6}$$

N_{eq} can be taken as the *Cyclic Index*, given a specified value of the equivalent constant-amplitude stress, $\Delta\sigma_{eq}$. The value of the equivalent cyclic stress is arbitrary. The authors of this article chose to define $\Delta\sigma_{eq}$ as 72% SMYS for API 5L X52 steel, which corresponds to 0.72 x 52.2 ksi = 37.58 ksi. Given this definition of the equivalent cyclic stress, the Cyclic Index corresponds to the equivalent number of 72% SMYS cycles per year in X52. It is necessary to define the index in terms of an *absolute* stress (37.58 ksi in this case) rather than a percentage of SMYS. It is convenient to set this reference stress to the allowable hoop stress for X52 because this grade is roughly in the middle of strength levels for API 5L steels. Since the Cyclic Index corresponds to an equivalent number of pressure cycles per year, it is proportional to the fatigue damage rate. In other words, the Cyclic Index can be viewed as a *pressure cycle speedometer*.

Table 2 lists the Cyclic Index for the TTO5 categories as a function of SMYS for common grades of API 5L steel. Note that a “Very Aggressive” rating for Grade A25 is equivalent to “Mild” cycling in X80. Moreover, an X80 pipeline operating in the “Very Aggressive” regime, as characterized by TTO5, would fail 32 times (1521/48) sooner than an A25 pipeline with a “Very Aggressive” rating. Thus Table 2 illustrates a serious shortcoming of the TTO5 pressure cycle rating method, where cyclic hoop stress is normalized by SMYS. As stated earlier, the *absolute magnitude* of cyclic stress governs fatigue crack propagation.

Figure 2 shows the monthly variation of the Cyclic Index at a pumping station discharge in a line constructed with X52 ERW pipe. This plot incorporates four years of pressure data. The severity of cyclic loading can vary significantly month to month.

TABLE 2.
Cyclic Index for the four TTO5 categories as a function of SMYS. The Paris exponent (m) = 3.

Grade	SMYS, ksi	Cyclic Index			
		Very Aggressive	Aggressive	Moderate	Mild
A25	25.4	48	12	4	2
B	35.2	130	32	12	5
X42	42.2	219	53	21	8
X52	52.2	415	101	39	16
X60	60.2	636	155	60	25
X70	70.3	1013	247	95	39
X80	80.5	1521	371	143	59

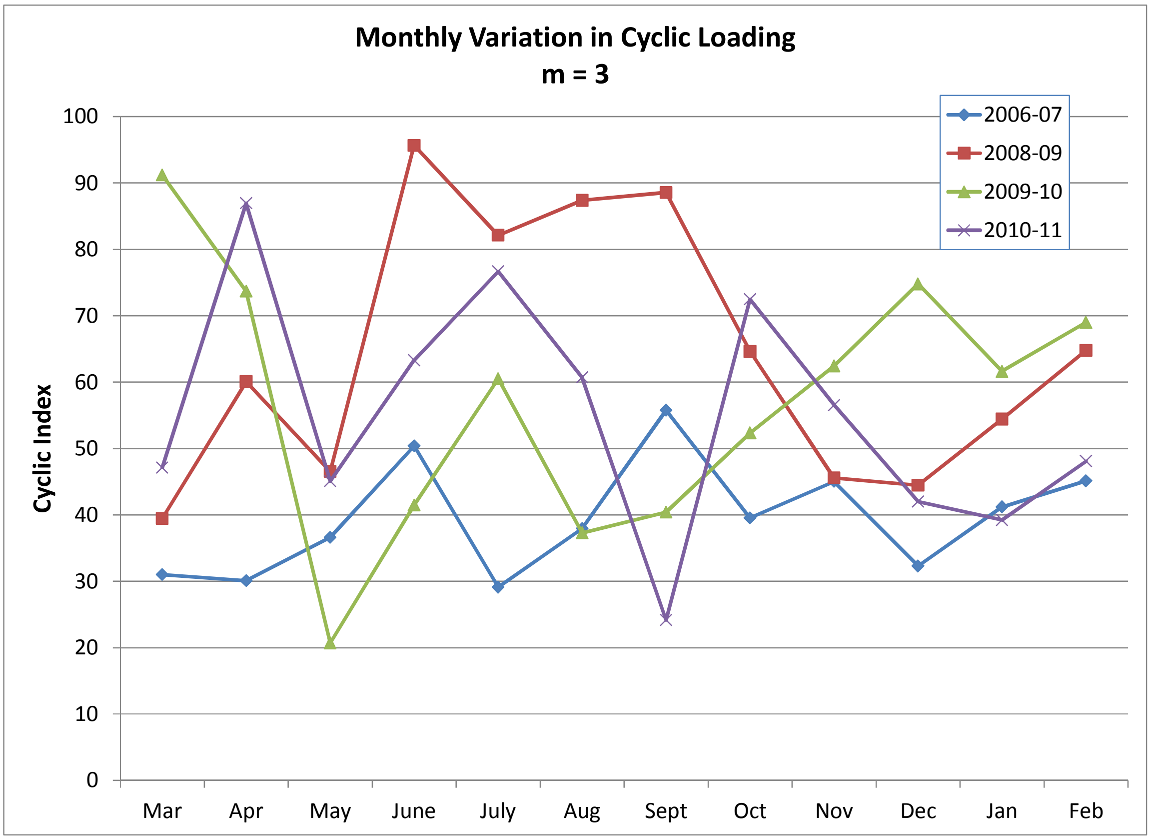

FIGURE 2. Monthly variation of the Cyclic Index at a pumping station discharge.

PROBABILISTIC PCFA MODEL

A major practical limitation of life prediction based on PCFA is that the outcome of such an analysis is highly sensitive to the input parameters. For example, uncertainties in crack sizing from ILI data can affect remaining life predictions by an order of magnitude.

Material properties are another source of uncertainty in a fatigue analysis, as life estimates are affected by tensile properties, fracture toughness, and Paris constants. Even if a pipe joint is excavated and subject to material testing, there is no assurance that the remaining joints in the line will have similar properties.

The traditional response of the pipeline industry to uncertainty in remaining life estimates is to make a series of worst-case assumptions. The resulting intervals for re-inspection or hydrostatic testing tend to be very conservative.

Probabilistic analysis is a viable alternative to worst-case deterministic analysis. Methods such as Monte Carlo simulation can account for uncertainties in the input parameters. A Monte Carlo simulation entails performing a deterministic analysis multiple times with various input values, which are chosen randomly from user-defined statistical distributions. The result is a plot of probability versus remaining life. The operator can then choose the re-inspection or re-test interval based on a tolerable failure probability.

Quest Integrity has recently developed a Monte Carlo-based PCFA model. Up to 9 input parameters can be treated as random variables. Figure 3 shows typical output from a Monte Carlo simulation.

The most important input to a PCFA, from the standpoint of its effect on predicted life, is the starting flaw size. In the Quest Integrity Monte Carlo model, the procedure for selecting the starting flaw dimensions depends on whether the integrity management plan calls for hydrostatic testing, ILI, or a combination of both. The various procedures for specifying the starting flaw dimensions in a given Monte Carlo simulation are described below.

Inferring Flaw Dimensions from Hydrostatic Testing

When a section of a pipeline passes a hydrostatic or spike test, it is assumed that the worst remaining flaw is slightly below the critical size for failure at the test pressure. The starting flaw size for PCFA is then set equal to the calculated critical flaw size. A critical flaw *curve* rather than a single value actually characterizes the largest cracks that could have survived the pressure test, as there is an infinite number of combinations of flaw depth and flaw length that are critical at the test pressure.

Given uncertainty in material properties such as yield strength and toughness, there are actually a range of possible critical flaw curves, as Fig. 4 illustrates. In a Monte Carlo trial, one of the possible curves is randomly selected based on the material properties for that particular trial. The red curve in Fig. 4 denotes the randomly selected critical flaw curve. Next, it is necessary to pick a value on the curve. This requires randomly choosing a flaw aspect (depth/length) ratio, as Fig. 5 illustrates. The starting flaw is then defined from the point on the curve corresponding to the chosen flaw aspect ratio. This flaw is used in the fatigue analysis, which may incorporate randomness in material properties and cyclic loading. This entire process is repeated for each Monte Carlo trial.

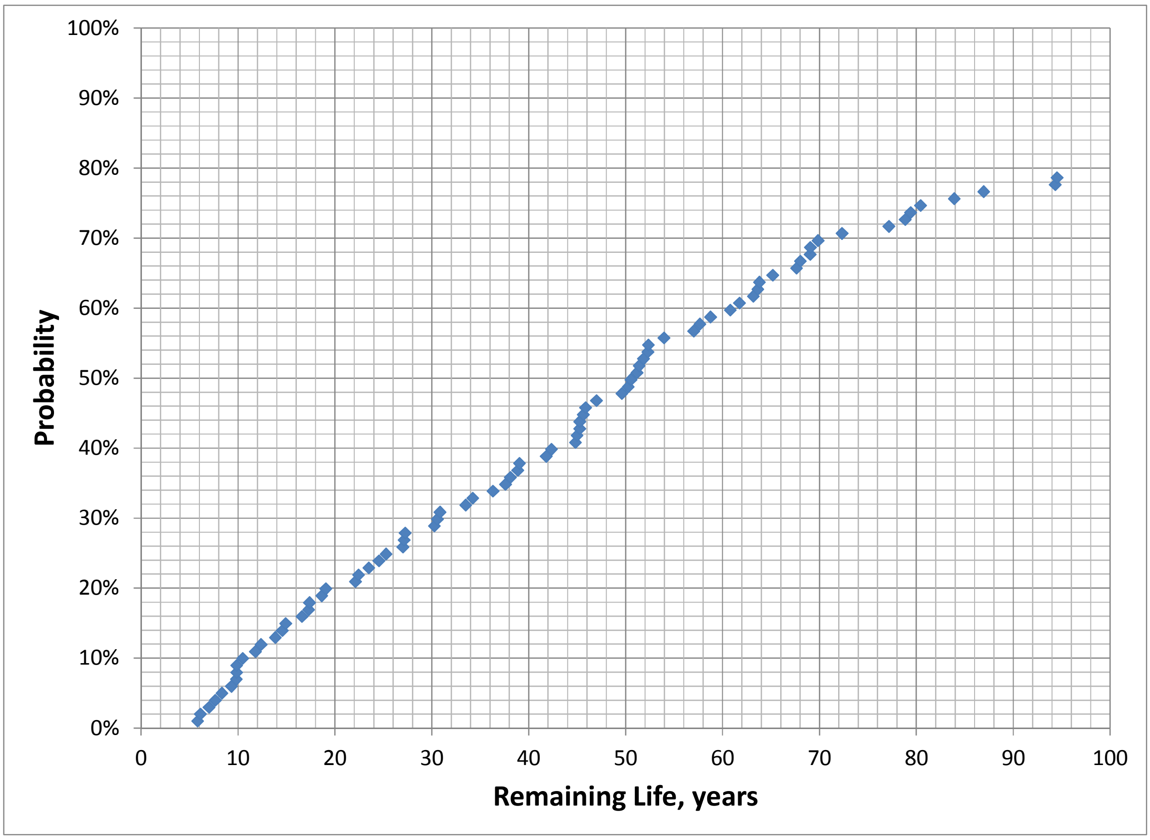

FIGURE 3. Typical output from the Monte Carlo PCFA model.

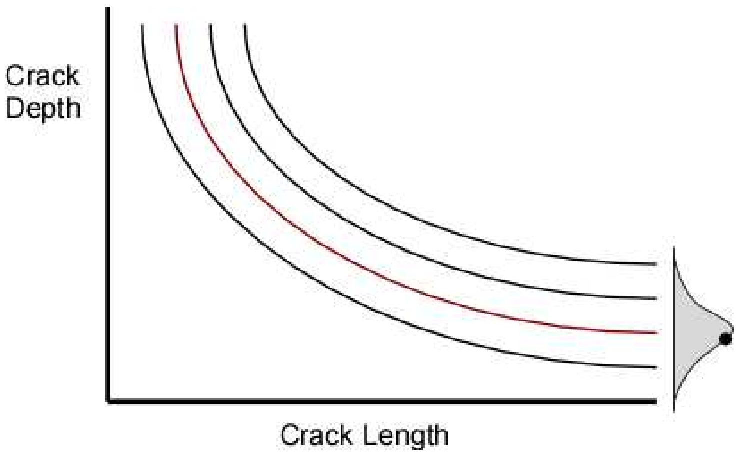

FIGURE 4. Family of critical flaw curves for a hydrostatic test, given uncertainty of input parameters to the fracture model. The red curve corresponds to the critical flaw curve selected in a given Monte Carlo trial.

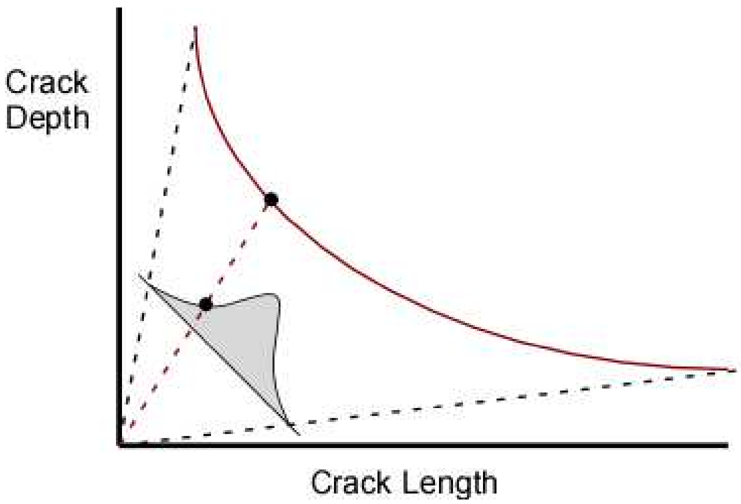

FIGURE 5. Selecting starting flaw dimensions from the critical flaw curve from Fig. 4. The flaw aspect ratio (depth/length) is treated as a random variable in the Monte Carlo analysis.

Inferring Flaw Dimensions from ILI

When an ILI crack tool is run on a section of pipeline, there is a finite probability that some flaws will not be detected. Assuming that all detected flaws are remediated, the worst remaining undetected flaw can be inferred from the probability of detection (POD) characteristics of the ILI tool, which are illustrated in Fig. 6.

An ILI vendor will typically report separate POD specifications for flaw length and flaw depth. In a given Monte Carlo simulation, a random depth and length will be selected from the respective POD information. The result is the red L-shaped curve in Fig. 6. The starting flaw dimensions for the fatigue analysis are inferred from a random flaw aspect ratio, as Fig. 7 illustrates.

Combining ILI with Hydrostatic Testing

When pressure testing is combined with ILI, the Quest Integrity Monte Carlo model can quantify the effect on the probability versus remaining life curve. In theory, applying both ILI and pressure testing should lead to a longer safe interval between testing/inspection.

Figure 8 illustrates a starting flaw curve, given the application of both ILI and pressure testing. The curves for the respective methods are computed separately, as shown in Figs. 4 and 6, and the combined curve is defined as the minimum of the two at each point. The solid red curve in Fig. 8 represents the combined starting flaw curve. The starting flaw dimensions are then inferred from the randomized flaw aspect ratio, as before.

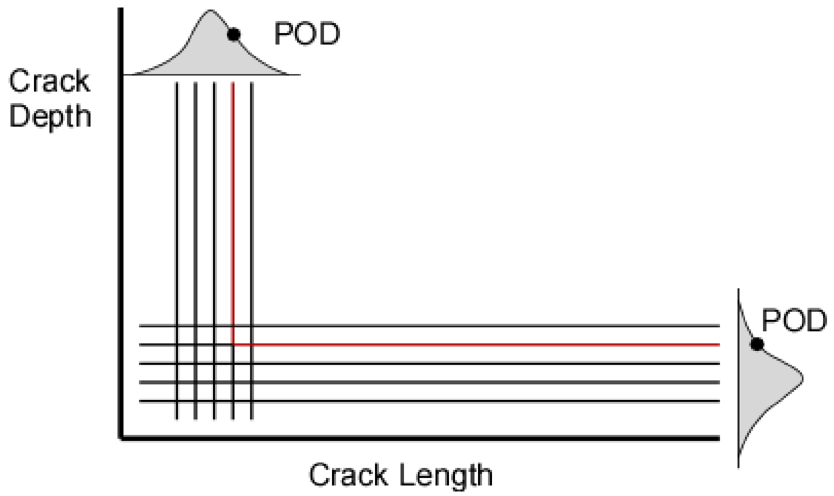

FIGURE 6. Determining the maximum undetected flaw length and depth based on probability of detection (POD) specifications for the ILI tool. The red L-shaped curve represents the locus of possible initial flaw dimensions for a given Monte Carlo trial.

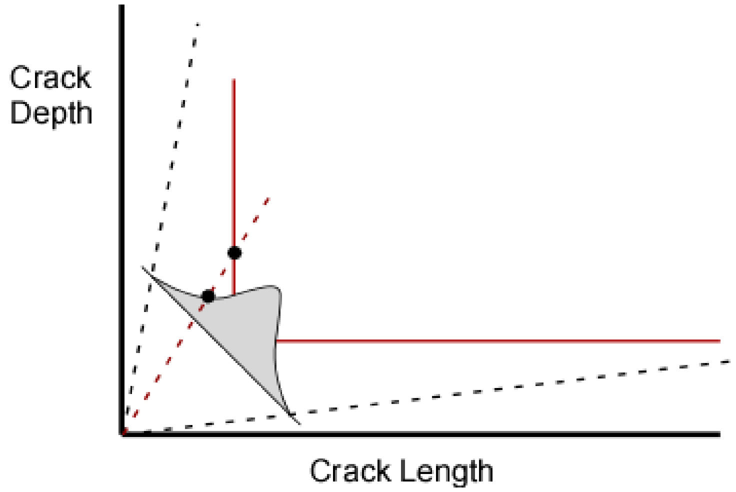

FIGURE 7. Selecting the starting flaw dimensions from the L-shaped curve from Fig. 6. The flaw aspect ratio is treated as a random variable, similar to Fig. 5.

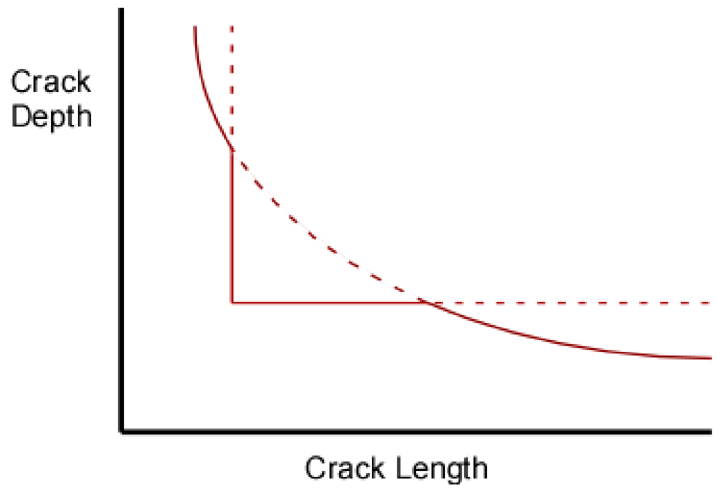

FIGURE 8. Starting flaw curve for ILI + hydrotesting, obtained by combining Figs. 4 and 6.

SEAM WELD INTEGRITY MANAGEMENT

The goal of the any integrity assessment is to provide information in order to make informed decisions that will successfully manage the risk related to that integrity threat. This involves performing analyses that develop a more complete understanding of the threat profiles throughout the pipeline. Seam welds in cyclic service are no different in that respect. The challenge with seam weld assessments are how to effectively manage the large amounts of pressure data required to perform the analyses and how to best integrate uncertainties in the data into the assessment. Advances in the application of seam weld assessments to integrity management will be discussed in this section.

Application of the Cyclic Index

Since pressure loading is the driving force for fatigue crack growth it is very helpful to understand both the amount of cyclic loading and whether it is getting more severe. A comparison of cyclic loading between lines also helps to identify those with a higher risk for seam weld fatigue failures.

A further issue with the benchmark pressure cycle count in TTO5 is that it is impractical to use. It is difficult to fit a complex pressure regime into one of the four categories and therefore to properly understand the impact on remaining life a pressure cycle fatigue analysis would need to be completed.

As the Cyclic Index turns a complex pressure regime into a single quantitative value, it is very helpful for either trending or comparison purposes. Figure 9 shows both the monthly variation in cyclic loading and the trend which in this case is to an increase loading. The cyclic index is proportional to fatigue growth where, for example, a doubling in index value equates to about twice the rate of fatigue growth and half the remaining life.

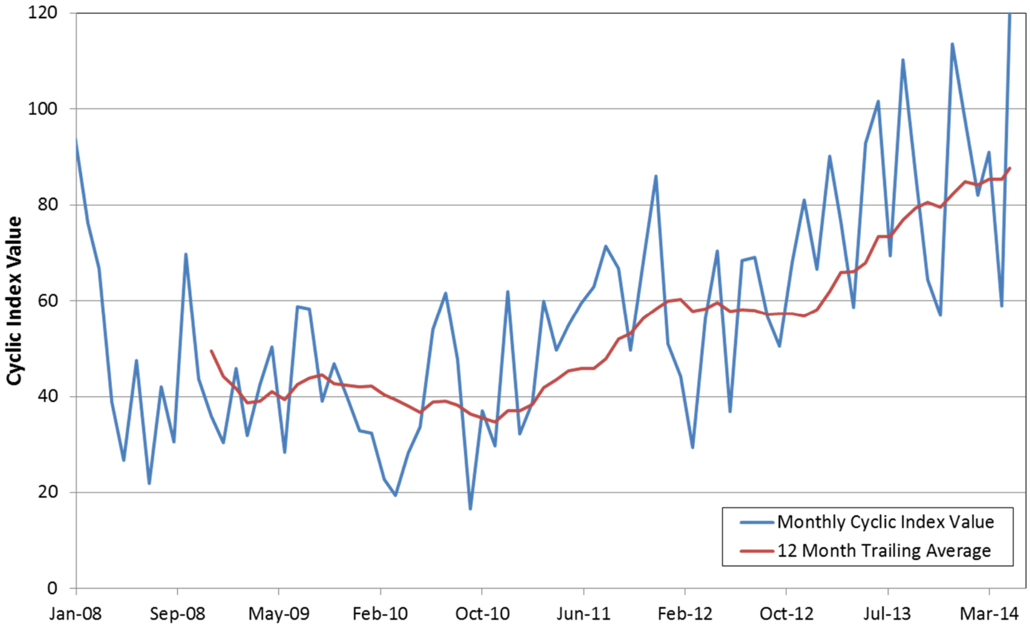

FIGURE 9. Monthly cyclic index values for a pipeline including a trailing 12-month average showing an increase in pressure cycle loading.

Hydrotest vs. ILI Decision Making

The outcome of a complete seam weld assessment is the remaining life of a critical flaw, or set of flaws, on a pipeline. This remaining life value, with the correct safety factor, is what is used to determine the re-inspection interval of a pipeline. This leads to the often difficult decision between inspection methodologies: hydrotest, crack in-line inspection (ILI) or both.

Each individual method has its strengths and weaknesses. A hydrotest is proof positive of the integrity of the pipeline, but does not provide any information about the number or size of cracks remaining on the pipeline. A crack in-line inspection provides information about the crack population that can be used to develop an anomaly response program but carries some uncertainty due to each tool's flaw detection limitations and measurement inaccuracies. To help weigh the relative benefits of each methodology the flaws that will be either destructively removed, for hydrotest, or detected, for ILI, can be compared to each other.

Critical flaw curves are used to represent flaws that are critical at both maximum operating and test pressures. Any flaw that is greater than the critical flaw curves at the maximum operating pressure will not have survived the hydrotest.

An ILI detectability window represents flaws have been reliably detected by the tool. The analysis can be first performed using the probability of detection specified by the vendor and further refined based on verification results.

The relative effectiveness of both methods can be compared by overlaying the critical crack curves with the tool detectability window. To find all critical anomalies the ILI needs to detect flaws at the MOP critical flaw curve. If the ILI detectability window extends beyond the critical flaw pressure critical flaw curve then it is more sensitive to flaws than the hydrotest is. In the example shown in Figure 10 the ILI anomaly detectability window extends beyond the critical crack curve for the hydrotest indicating that ILI has the potential to identify smaller cracks then the hydrotest. Noted that the relative effectiveness of hydrotesting, ILI, or a combination of the two can also assessed using the probabilistic model described earlier.

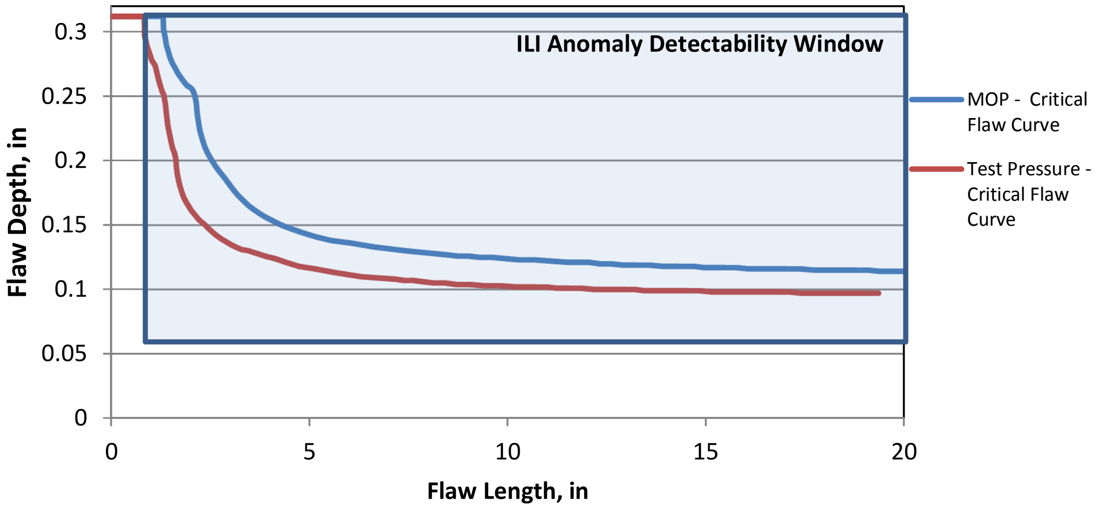

FIGURE 10. This chart shows the relative merits of an ILI inspection and an ILI survey by comparing the detectability window and hydrotest and MOP critical flaw curves

Pacifica™ Integrity Management Software Platform.
To both make PCFA assessments easier to complete and incorporate the new assessment methodologies a new analysis platform was required. Such a platform needs to effectively manage the large amounts of pressure data and pipeline data and still be able to perform the analyses using seam weld integrity management best practices, including the innovations discussed in this paper.

Pacifica has been designed using an innovative database structure that can be automated to import pressure data which is then stored for the lifetime of the pipeline. Storing the pressure data means that rainflow counting, turning the pressure data into pressure cycles, only needs to be done once and then can also be stored in the database. Making the more mundane tasks that are part of PCFA easier allows more time to be spent on analyses. Figure 11 shows an overview of its architecture and workflow.

The measure of the effectiveness of assessment software is not limited to its ability to give accurate results for an analysis, but is better defined by its ability to provide the information required to make solid integrity decisions. Keeping this in mind, Pacifica has been developed with a pipeline operator to ensure that the analyses that are available support integrity management decision making.

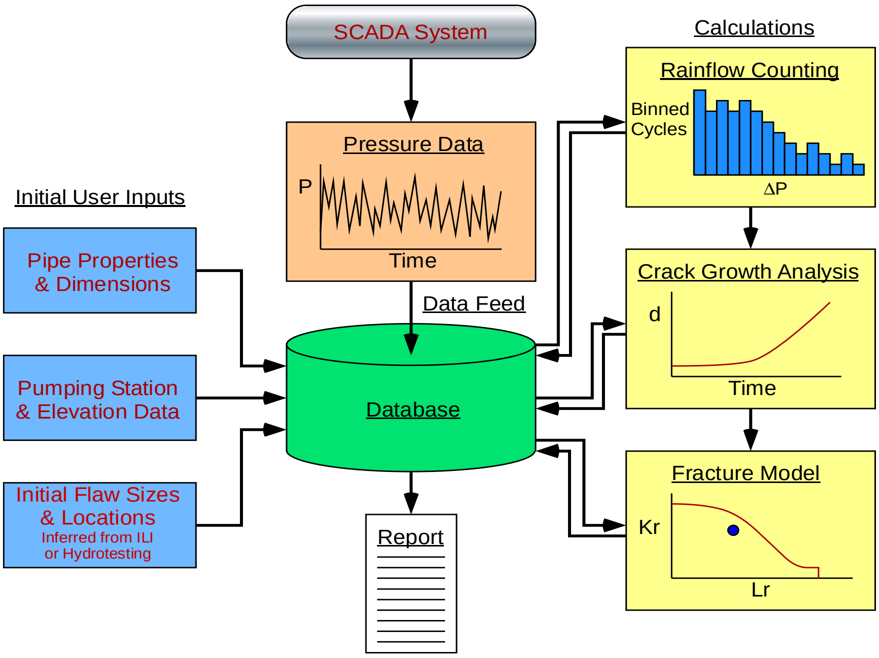

FIGURE 11. An overview of Pacifica architecture and workflow.

CONCLUDING REMARKS

To effectively manage the threat of fatigue in seam welds on liquid lines, the assessment needs to be based on solid engineering theory. As we continue to learn more about seam weld failures and apply that knowledge to improve the assessments, it is important that those assessments become incorporated into integrity management best practices.

A pressure cycle fatigue assessment often starts and always ends with the fracture model. Using a fracture model that will predict failure pressures as accurately as possible across the range of material properties is the single most important element to making the assessment predict actual line behavior. Fracture models that have traditionally been used by the pipeline industry suffer from series shortcomings [5], but improved models are now available [2, 3]. Even with the best fracture model, however, uncertainties in material properties, flaw dimensions and other input parameters result in uncertainties in predicted time to failure. A probabilistic analysis, such as the Monte Carlo model described herein, is an effective method to handle such uncertainties.

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