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Division II

BENCHMARKING PROBABILISTIC ANALYSIS LBB CODES AGAINST DETERMINISTIC LBB ANALYSIS

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BACKGROUND

In piping systems or vessels, a leak (while an event to avoid) can be a harbinger of an impending catastrophic event. Determining the size of the damage at the time of a detectable leak can be used to increase the safety of the system. If the damage size is substantially smaller than the critical damage size then once a leak is detected the system can be shut down and repaired before the catastrophic event occurs. This evaluation is called Leak Before Break (LBB) analysis (Scot, Olson, & Wilkowski, 2002).

While several industries can benefit from this type of analysis this paper focuses on nuclear piping in light water reactors (LWRs). For this application the United States Nuclear Regulatory Commission (US NRC) had developed a methodology for performing LBB analysis as early as 1984 (The Pipe Break Task Group, 1984). Until recently piping codes for damage initiation and growth have been deterministic, although there were several codes that were developed that dealt with fatigue primarily and circumferential cracks for example, (Bishop, 1997), (Chapman, 1998), (Harris, 1992). Several codes expanded the analysis for corrosion mechanisms including (Duan, Wang, & Kozluk, 2013), (Itoh, Osakbe, Onizawa, & Oshimura, 2012), (Kurth R. , et al., 2017). Since 2008 a program, jointly funded by the US NRC and the Electric Power Research Institute (EPRI), known as xLPR (extremely Low Probability of Rupture (Rudland, et al., 2010)), has been developed together with the pre-processor program, funded by the US NRC, PROMETHEUS (PROBabilistic METHods for Evaluating and Understanding Structures) (Kurth & Sallaberry, 2018), to perform probabilistic modelling of the initiation and growth of damage in pressure retaining boundaries, outside of the reactor vessel, in a probabilistic framework. This paper presents a comparison of the deterministic LBB evaluation with a probabilistic LBB analysis.

PROBLEM DEFINITION

Many scenarios, damage mechanisms (e.g. fatigue, stress corrosion cracking), and events (e.g. earthquakes, floods, or loss of on-site power) can impact a LBB assessment. This paper focuses on damage due to primary water stress corrosion cracking (PWSCC) in a dissimilar metal weld in the primary water piping system of a nuclear power plant.

The historical assessments performed focused on determining the size of a crack when the leak rate reaches 10 gallons per minute (gpm) (6.309×10^{-4} m^3/s) compared to the crack size at the failure of the pipe. To “pass” the LBB criterion this ratio must be greater than 2, requiring a margin factor of 2 in the crack size between detection and failure.

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Several conservatisms are implicit in this criterion. First, it is widely believed that with current technology, the leak detection capability in a LWR is 1 gpm or lower. Thus, assuming a 10 gpm limit is highly conservative for detection of the leak prior to failure. Second, using the criterion that the crack size at failure must be at least twice as large as the size at a 10 gpm leakage rate provides time for the leaking pipe to be detected and, as importantly, time to shut the plant down before pipe ruptures.

PROBABILISTIC RESULTS

The quantity of interest for LBB is the *critical ratio,* which is defined as

$$\boldsymbol{R = \frac{c_{rupture}}{c_{10\ gpm}}} \tag{1}$$

where $\boldsymbol{c_{rupture}}$ is the crack length at pipe rupture

$$\boldsymbol{c_{rupture} = \theta_{max} R_{inner}} \tag{2}$$

θ_{max} is the crack length at rupture estimated by the xLPR code (expressed in radian) and R_{inner} is the pipe inner diameter. $\boldsymbol{c_{10\ gpm}}$ is the crack length when the leak rate reaches 10 gpm. The current xLPR 2.0 version does not output the crack length at 10 gpm so we use PROMETHEUS to output the crack length at the time step that the leak rate exceeds 9.8 gpm.[4] Figure 1 displays the estimation of the ratio $\boldsymbol{R}$ using the crack length when Through Wall Crack (TWC) occurs (blue diamonds) as well as the ratio $\boldsymbol{R}$ when the leak rate reaches 10 gpm (red circles) on a generic set of data with consequent uncertainty.

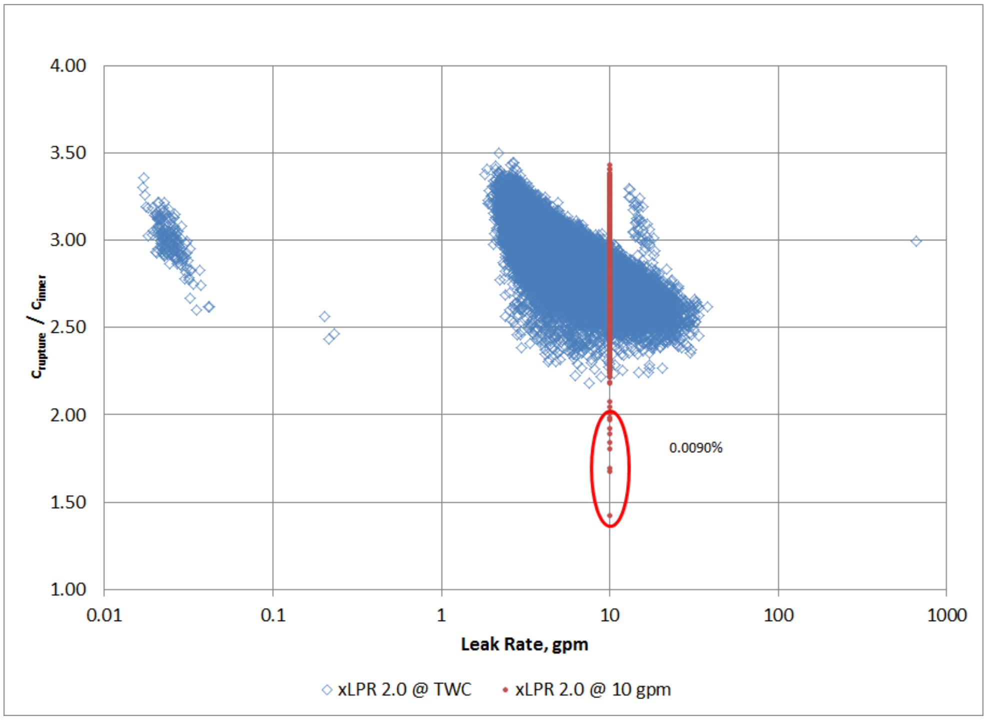

Figure 1: Comparison of the critical crack length to the crack length at time of TWC or 10 gpm leak rate versus leak rate

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[4] We use a number slightly lower than 10 gpm to catch the simulations where the leak rate is changing quickly

As Figure 1 illustrates there is some probability of the LBB criterion being violated with a ***R*** value lower than 2 (highlighted by the red ellipsoid). Such result is not unexpected when using generic data with large uncertainty. The possible variability in the inputs (and the combination of inputs) is too large to be applied to a single weld at a specific plant.

To identify the culprit of LBB criterion failing, a sensitivity study is performed for the uncertain input variables. The results of this study are shown in Figure 2.

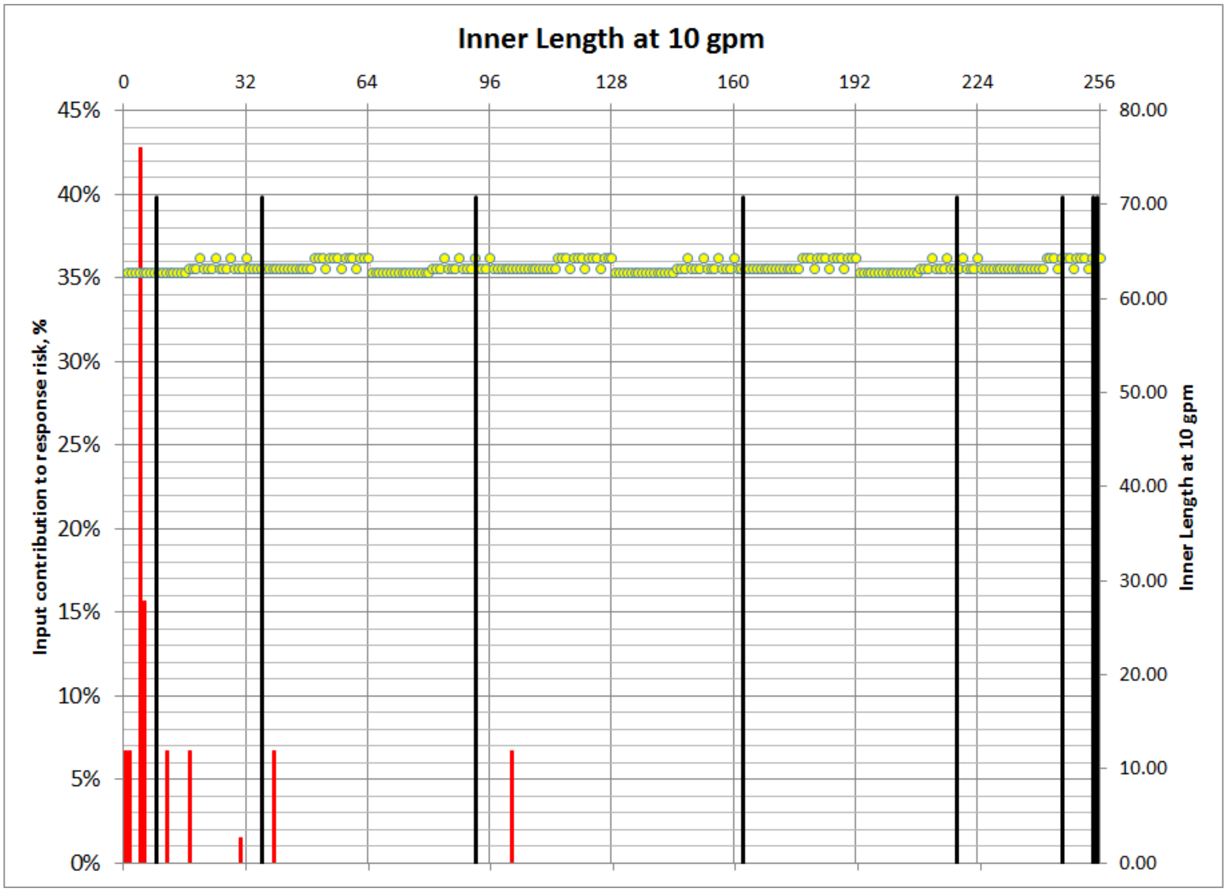

Figure 2: Full factorial design results for the inner length at 10 gpm

Figure 2 presents a full factorial decomposition of the influence of the selected uncertain variables toward the output of interest (the ratio ***R***). The left ordinate is the percent contribution to the response uncertainty by every variable and all interactions, shown as red bars (each bar is associated with one input or one combination of distinct inputs). The black bars divide the plot among the main effects, two factor interactions, three factor interactions, etc. As we see in Figure 2 the main effects account for about 71% (sum of the red lines in the first quadrant) of the response uncertainty, two factor interactions for 16% (sum of the red lines in the second quadrant), three factor interactions for 6.5% and four factor interactions for 6.5%. In all, about 99% of the response variance is account for by the yield strength (for the left and right pipes in a Dissimilar Metal Weld) and Young's modulus (left and right). Since these variables are the ones driving the ratio results, they will be studied in an aleatory/epistemic analysis in the case of LBB criterion failure.

CONSERVATISM IN CURRENT LBB ANALYSIS

Once the key drivers have been identified we can now examine the conservatism introduced into the standard nuclear piping LBB analysis. In Figure 3 we plot the probability of the ratio of the inner crack length at rupture to the inner crack length at leakage for two different leakage levels. The first using a 1 gallon per minute (gpm) detection level (black curve), and a second using 10gpm (red curve).

All the calculations are performed with the assumption that a crack, whose initial size is treated as uncertain, exists at time zero. The LBB ratio thus reflects a conditional risk which is higher than the true risk (that would be weighted with the probability of having a crack occurring).

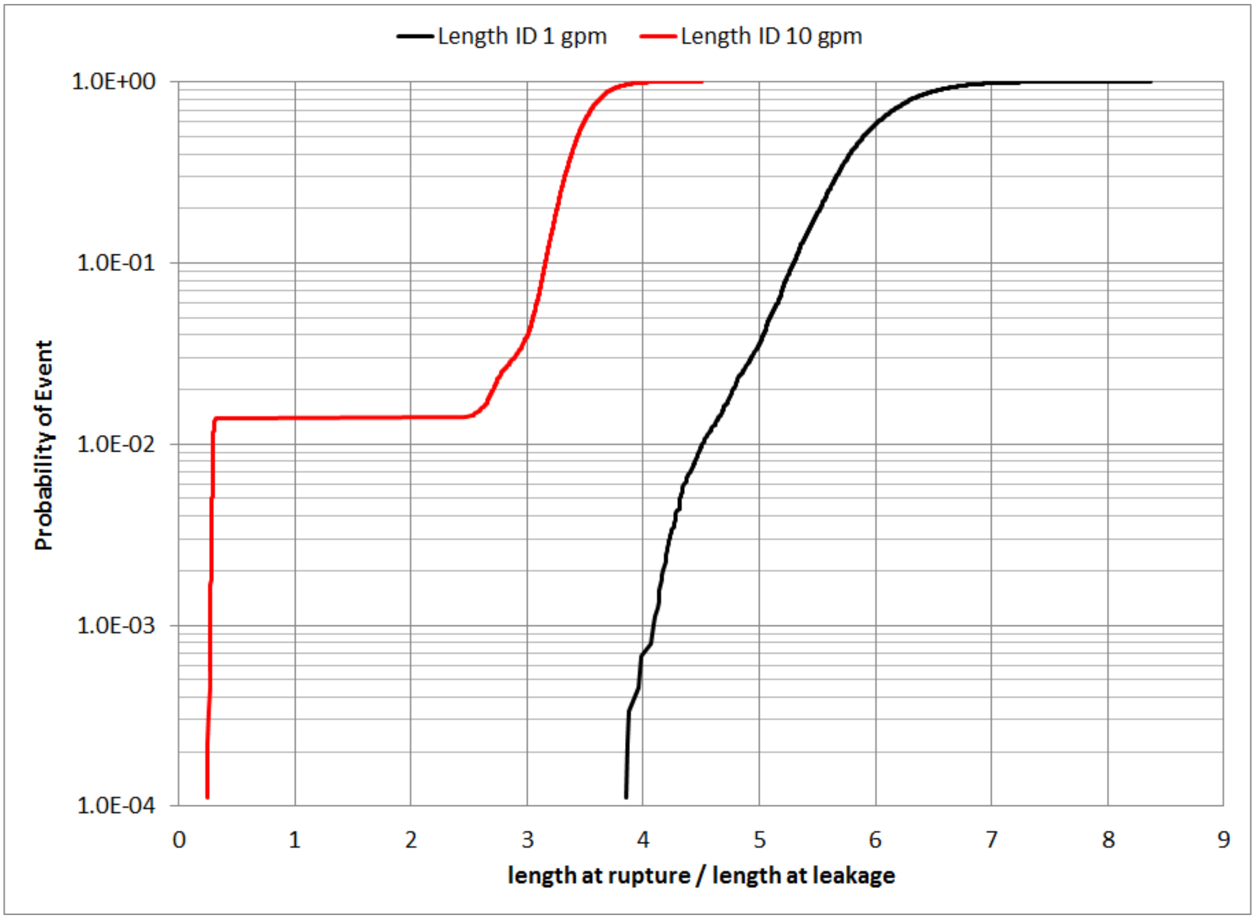

Figure 3 Comparison of the ratio of the inner crack length at rupture to the inner crack length at leakage for two different leakage levels

As the curves in Figure 3 indicate the use of a 10 gpm detection level is overly conservative for the calculation of the probability of LBB. It is important to note that the conservative assumption of using twice the crack length at the specified leakage rate level has been removed since a probabilistic analysis is being performed based on uncertain inputs. Thus, multiplying the calculated crack length at the specified leakage level is equivalent to implying that we are uncertain about the individual inputs uncertainty. If this is truly the case then an epistemic-aleatory analysis should be performed to treat this type of uncertainty, not an arbitrary multiplier to the best estimate result.

One of the requirements in the standard deterministic LBB analysis is to add the safe shutdown earthquake (SSE) loading to the stability load. Figure 4 displays these additional curves with inclusion of seismic loads for the 10 gpm (blue curve) and 1 gpm (red curve) detectable leak rate. At the time of the analyses the SSE load had not been defined so we added a load equal to twice the normal operating load effective moment.

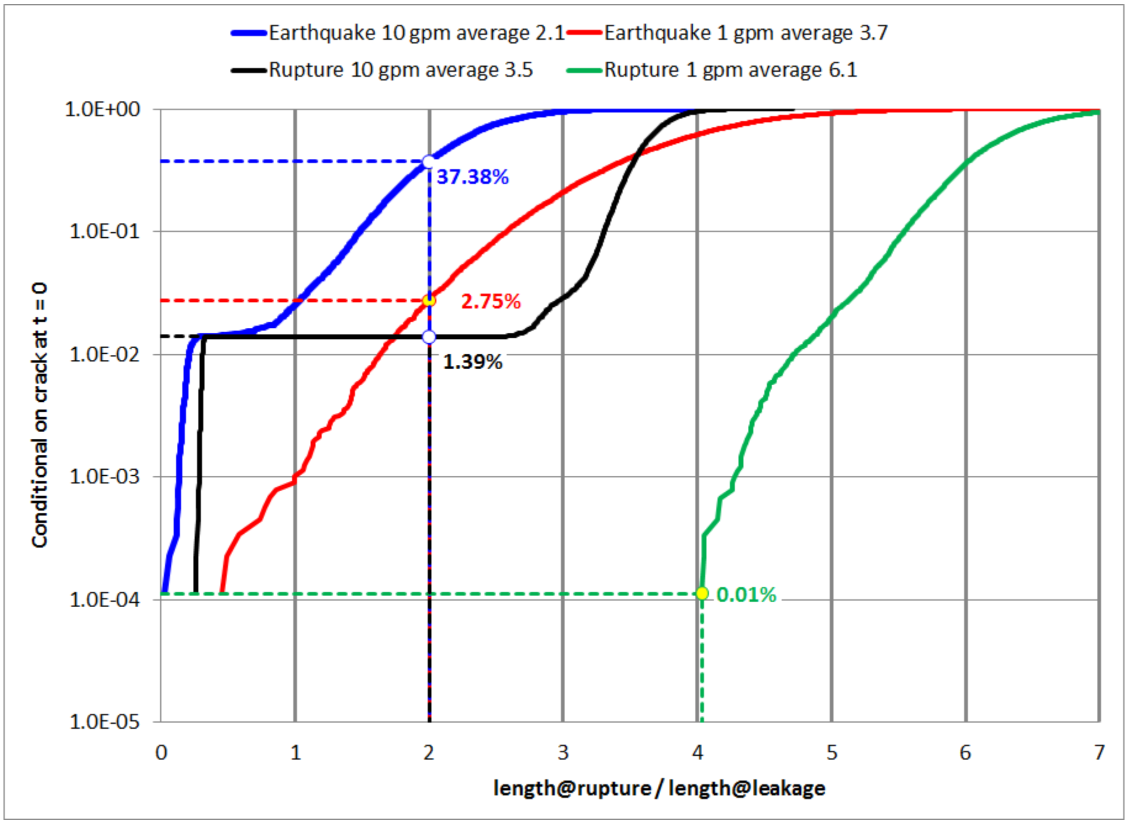

Figure 4 Comparison of LBB criterion with earthquake loading and without earthquake loading to 1 gpm and 10 gpm detectable limits

The blue curve shows the cumulative distribution function (CDF) for this ratio when the earthquake load is included and the detectable leak rate is 10 gpm. As the legend indicates, the average value of this ratio is 2.1. The curve also shows the probability that the ratio is less than 2 is 37.4%. A regulatory decision based on the mean (equal to 2.1 thus higher than the threshold of 2) would be considered as borderline acceptable. While a more traditional probabilistic approach looking at the percentage of realization leading to a ratio below 2 (37.4%) is likely to consider the risk too high.

When a more realistic detection rate of 1gpm is used (red curve in Figure 4), the average ratio is 3.7 while the probability of the ratio being less than 2 is 2.7%. These metrics are more within the range of acceptable risk for LBB.

Figure 4 repeats the results presented in Figure 3 when the earthquake load is not included. In this case 10 gpm ratio has a lower average than with the earthquake load (as expected), or probability of having a ratio lower than 2. However it is worthwhile noting that the probability of having a ratio lower than 1 (representing break before detectable leak) is higher than with the 1 gpm including earthquake load. This outlines that the 10 gpm detection limit may be too conservative for a probabilistic analysis. It was appropriate for a deterministic analysis that was representing uncertainty with such high conservatism, but is equivalent to double counting uncertainty in a probabilistic case.

When the rupture case is run using a 1 gpm leak rate then the lowest value of the ratio of rupture length to the length at 1 gpm is slightly greater than 4, leading to a passing of the LBB criteria.

PROBABILISTIC ANALYSIS OF TIME BETWEEN DETECTABLE LEAK AND RUPTURE

The initial deterministic analysis is also static, meaning that it compares cracks length at two representative events (leak rate and rupture) without considering the time occurring between these two events. In reality, the remaining life time between detected leak and rupture is an important aspect of the LBB analysis as it informs on how much time is available for the repair.

In this section we consider the delay between the time that a crack experiences a 1 gpm leak rate and the time of rupture. These comparisons are shown in Figure 5 with a crack always occurring at time 0 (blue curve) and with the crack initiation treated probabilistically (red curve). What is found is that *for an existing crack at time zero*, the probability of having only one month separation between the leakage size at 1 gpm and rupture is about 1 in 10,000. When 500,000 simulations are run with the crack initiation model there were no instances of any delay less than 6 months.

In conclusion, the traditional assumption of an existing crack (or event Through Wall Crack) at time zero adds more conservatism which can be reduced when using a probabilistic model, in order to estimate a more realistic metric.

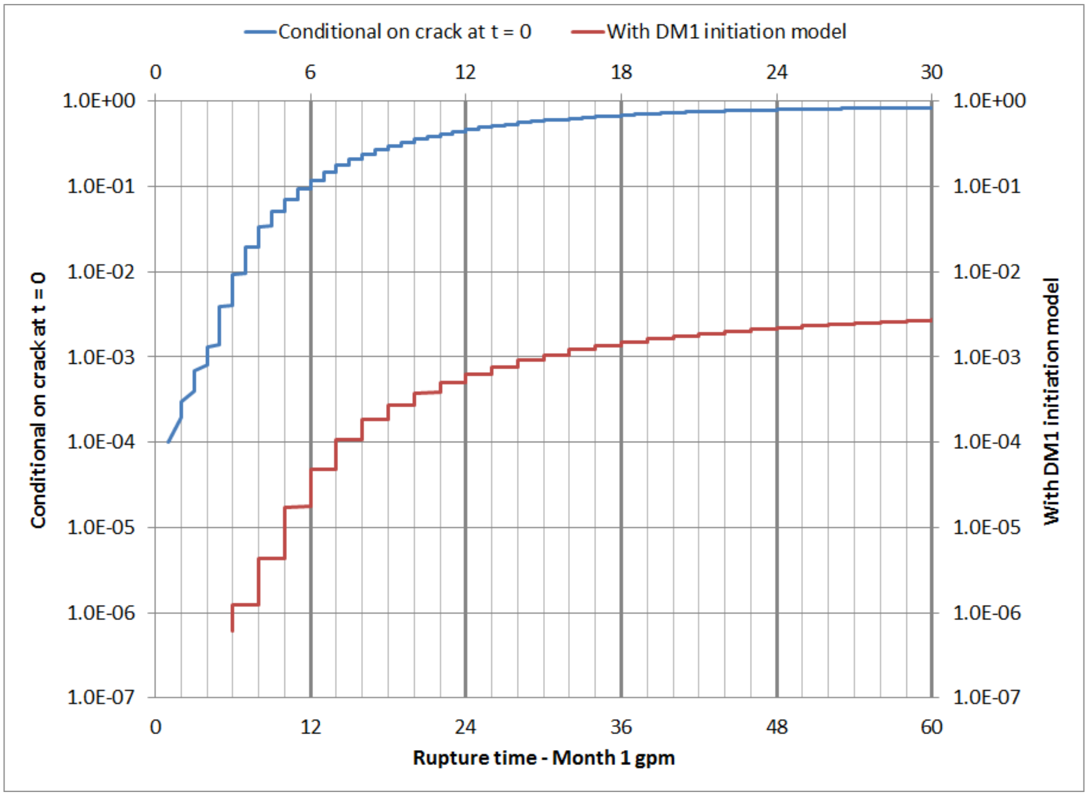

Figure 5 Comparison of the time between rupture and a 1 gpm leak rate in months

CONCLUSION

Deterministic analyses of LBB often rely on conservative assumptions to include an additional safety protection in the estimate of leak before break event. With a probabilistic approach, such conservatism can be reduced to generate more “realistic” results.

While in previous analyses of pipe rupture over time events did not find yield and ultimate strength of the material to be important factors, they drive here the uncertainty in LBB ratio due to their impact on COD and stress-strain relationship (which are important for leak rate calculations). This result is an important reminder that the significance of parameters change depending on the output of interest.

The probabilistic approach gives the possibility of identifying these major (uncertain) factors influencing the estimate of the quantity of interest via sensitivity analyses techniques. Focusing on a better representation of those specific parameters (i.e., developed for the plant specific application) should lead to more realistic assumptions and less uncertainty, thus increasing confidence in a pass or fail result. Overall, the probabilistic approach gives the decision maker a better understanding of the issues in the case of LBB criterion failure and higher confidence in the decision.

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