Reliability analysis of low alloy ferritic piping steels
A- Baseline case

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ABSTRACT. *Our study aims at the modifications of pc-PRAISE to provide capabilities for probabilistic analysis of fatigue-crack initiation and growth. This expanded version of the software is referred to as Version 4.2. The PRAISE code was originally developed to provide a probabilistic treatment of the growth of crack-like weld defects in piping due to cyclic loading (Harris et al. 1981; Lim 1981). The purpose of the efforts reported herein is to expand the capabilities of PRAISE to include a probabilistic treatment of fatigue-crack initiation in low alloy ferritic piping steels. The current capabilities for analyzing fatigue-crack growth are then used to continue the calculations to crack penetration of the pipe wall.*

1.INTRODUCTION

Piping systems experience fatigue damage as a result of anticipated plant transients (e.g. rapid cooling of the piping during auxiliary feed water initiation following a scram) and because of unanticipated transients (e.g. check valve leakage) [1].This paper describes the probabilistic fracture mechanics computer code and structural mechanics modelling approach used to simulate the effects of these cyclic fatigue stresses on the reliability of reactor piping.
Probabilistic fracture mechanics (PFM) calculations often assume that the stress state in the pipe wall is uniform through the wall thickness. This approach is appropriate for stresses as a result of internal pressure and for bending stresses as a result of the thermal expansion of pipe systems, but does not address through-wall stress gradient as a result of radial thermal gradients or geometric discontinuities [2].
This paper describes modifications to pc-PRAISE to provide capabilities for probabilistic analysis of fatigue-crack initiation and growth. This expanded version of the software is referred to as Version 4.2. The PRAISE code was originally developed to provide a probabilistic treatment of the growth of crack-like weld defects in piping due to cyclic loading [3]. This treatment of fatigue-crack growth was later expanded to include the initiation and growth of stress corrosion cracks [4]. The software was then

made to run on a personal computer for ease and economy of use [5]. The purpose of the efforts reported herein is to expand the capabilities of PRAISE to include a probabilistic treatment of fatigue-crack initiation. The current capabilities for analyzing fatigue-crack growth are then used to calculate the crack penetration in the pipe wall. The schematic diagram of the steps in the piping reliability calculations by pc-PRAISE are presented in Fig. 1.

2. PRAISE Modifications to Consider Fatigue-Crack Initiation

The ANL crack initiation correlations were for cycles for the tensile load to drop by 25%. This corresponds to a crack of approximately 3 mm depth (0.12 in.) [6, 7].The specimen size was assumed to be about 2 in. (51.76mm) gouge length. The fatigue tests were performed under fully reversed loading (i.e., a mean load of zero). The subroutine provided by PNNL already had size-effect and surface-finish adjustments, but a single factor was considered to account for size regardless of size. The subroutine provides cycles to initiation for a given probability of initiation and set of conditions (material, cyclic stress, strain rate, oxygen level, and sulfur content).
The relations, should not be extrapolated beyond a probability of 0.02%" [6, 7]; hence, they are not suitable for initiation probabilities below about 2.10^{-4}.

Modifications were made to pc-PRAISE to consider the initiation of cracks and their subsequent growth to become through-wall. For initiation, the PNNL subroutine for initiation was used in conjunction with Monte Carlo simulation to estimate the probability of initiation as a function of time. The subroutine provides results for a constant stress amplitude, whereas the stress histories to be considered have cyclic stresses of different amplitudes. The Miner's rule was used to account for these more complex stress histories.

The cycles per year are equal to the cycles per 40-year life divided by 40; that is, the cycling rate is considered to be constant. A description of each transient is usually provided.

Since multiple initiation sites are employed, some adjustment should be made to the size/surface finish compensations made by ANL. A portion of the size/surface finish effect introduced by ANL is removed by multiplying each sampled initiation time by a constant between 1 (using the ANL size/surface finish factor) and 4 (using the ANL laboratory specimen correlations). Tire distribution of initiation time is determined for each of the specimens in a component. The initiation times in each specimen can either be independent or dependent. If dependent and no stress gradient, in each specimen a crack will initiates at the same time. So the cracks initiate completely around the circumference for a girth weld in a pipe. This leads to all leaks being double-ended pipe breaks. Hence, independent initiation is believed to be the most realistic.

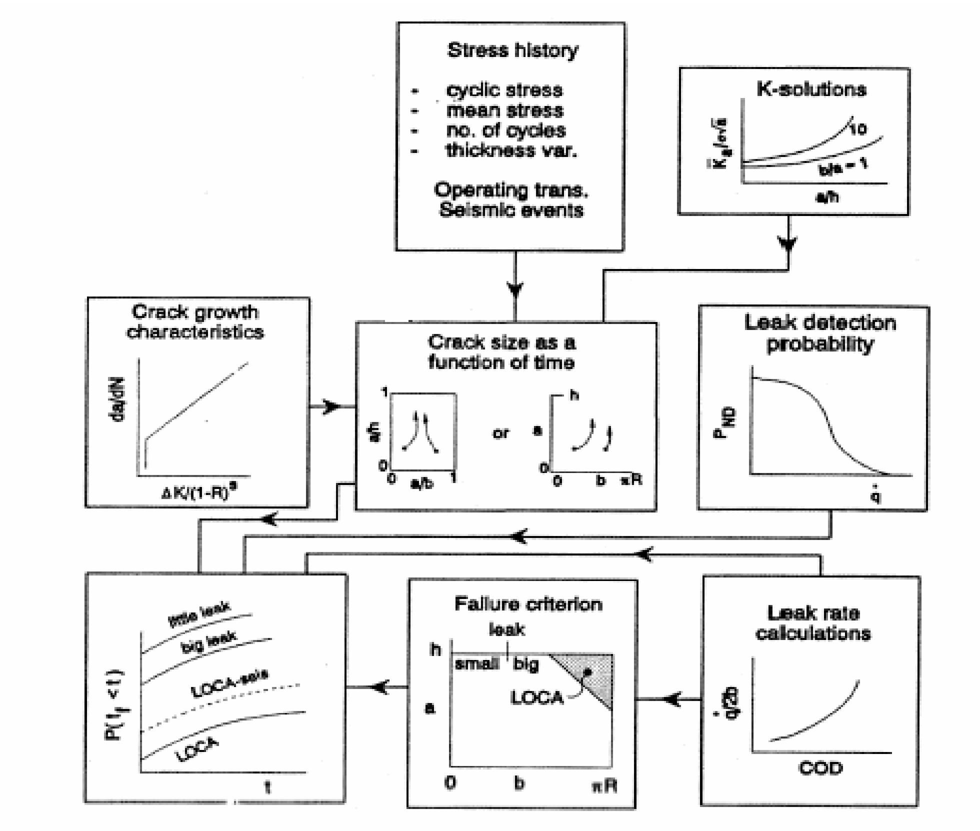

Figure1. Schematic diagram of piping failure probability calculation as perform- ed by pc-PRAISE. (Baseline case)

3. PRAISE Modifications for Crack Growth and Linking of Multiple Cracks

Once a crack initiates, pc-PRAISE calculates its subsequent growth. An initiated crack is considered to be 3 mm (0.12 in.) deep. It is still necessary to specify the surface length, $2b_0$, of the initiated crack. Although cracks that grow from a small defect will tend to be nearly semi-circular $(b_0 /a_0=1)$, the median length of an initiated crack is taken to be 7.6 mm (0.3 in.). This is believed to be conservative. The initial length is taken to be a random variable. The value of b_0 itself could be the random variable, and this is one alternative that was considered.

Taking b_0 to be lognormal with a median value of 7.6 mm (0.30 in.), it is then only necessary to define the shape parameter, μ, used by pc-PRAISE in order to define the complete distribution. A couple of items of interest in the distribution of b_0 are:

(1) The probability that *b/a*, at initiation is less than 1, which is physically unrealistic because the crack would then be tunnelling into the specimen.

(2) The probability that 2 b_0 would be greater titan the "specimen" size of 50.76 mm (2 in.).

Multiple cracks can initiate in a component and then grow to perhaps eventually coalesce. The criteria for linking of multiple cracks are already in pc-PRAISE to account for multiple initiations of stress corrosion cracks [4, 5]. The criteria are based on procedures in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code.

4. Correlations between Initiation and Growth Properties

It is conceivable that there is a correlation between the initiation and growth properties of the material. That is, if the crack-initiation characteristics are poor, then the growth characteristics are also poor. Pc-PRAISE provides for treating these properties as either independent or correlated. If they are correlated, then the one minus the sampled random number used for the initiation simulations is used for the growth relation.

5. Modification of Fatigue Crack Growth Relations for Ferritic Material

The fatigue-crack-growth characteristics for ferritic steels that are built into pc-PRAISE are for LWR environments. At very high values of ΔK, the crack growth relation falls below the air line for this material, which is physically unrealistic. For ferritic steel in air, the crack growth rate is given by:

$$\frac{da}{dN} = C(\Delta K)^{3.726} \qquad (1)$$

The exponent 3.726 comes from the ASME Boiler and Pressure Vessel Code.
No effect of R is considered for growth in air. C for the ASME air line is $2.67\ 10^{-11}$, which is an upper-bound value. Consider C to be log normally distributed with the ASME value being at the 95th percentile. The scatter in air will be less than in water. The median value of C can be evaluated, which leads to $C_{50} = 1.10\ 10^{-11}$.
To analyze fatigue crack growth in ferritic materials in water, a sample is drawn for the fatigue crack growth rate in water. The same random number is used to sample the fatigue crack growth rate in air. The crack growth rate is then taken to be the largest of the two.

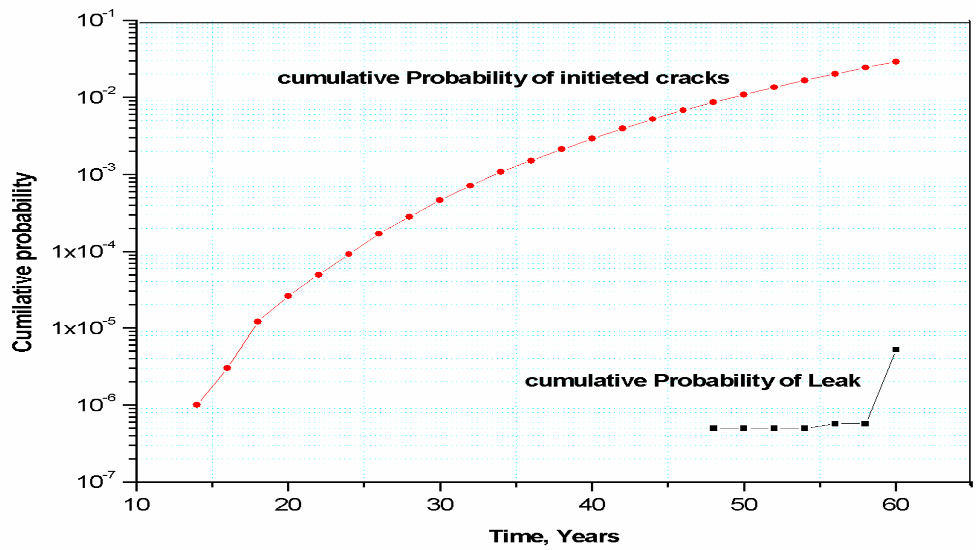

Figure 2. Cumulative failure probability as functions of time.

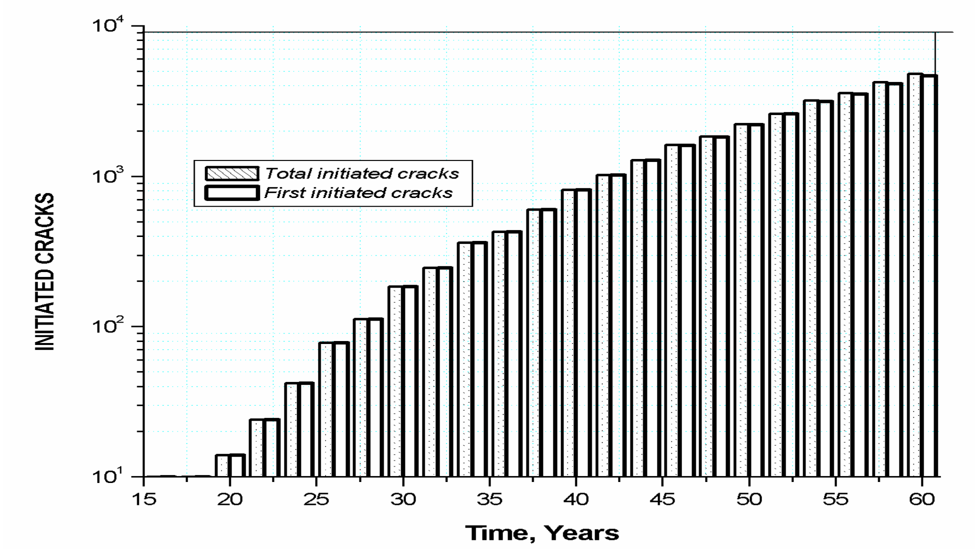

Figure 3. Crack initiation information from pc-Praise

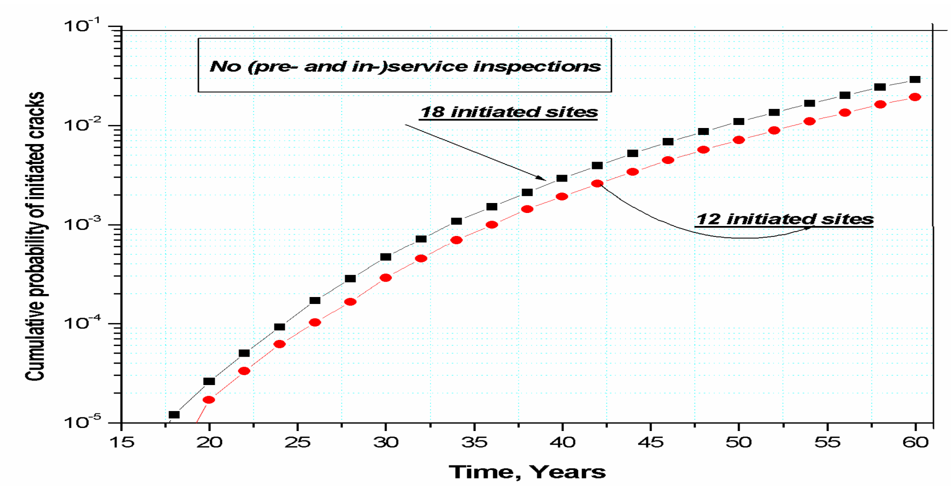

Figure 4. Effect of initiation site number on the cumulative failure probability

6. Example

The example problem of the previous section was analyzed using 18 initiation sites with a multiplier on t, of 3 and using (b_0-a_0) as the random variable describing the size of the initiated cracks.

7. Probability Result

In addition to probability of crack initiation, the probability of a leak (through-wall crack), is evaluated. Analyses were performed for no circumferential variation of the stresses. The results provide information on the relative leak-to-break probability for situations with and without variations of stress on the surface. Such information is useful in leak-before-break assessments.

For no circumferential stress variation, the stresses were taken to be axisymmetric, and the results are for times extending to 60 years. Fig. 2 provides a plot of these results. No results are plotted for the DEPB probability because no such failures occurred in the 100 trials performed. Provisions were added to the pc-PRAISE output to summarize the linking of cracks, which is described here. The results for this example problem with no stress gradient are considered. Fig. 3 provides an example of the information in pc-PRAISE on crack initiations, and a summary of crack initiation and linking. Such results are printed out. The effects of the number of initiated cracks sites are shown in Fig. 4.

For each evaluation time that is a multiple of 10. Hence, the crack-linking information is printed out for 20, 40, 50 and 60 years. Table1 includes the crack-linking information at 60 years. The results are summarized on a crack-by-crack basis, so information is lost regarding cracks on a weld-by-weld (trial-by-trial) basis.

Cracks in the depth range of 0.95<a/h< 99% are mostly through-wall cracks, which are of particular interest. Table entries for this range of depths provide information on the length distribution of through-wall cracks and how many cracks linked to form them. Any cracks that grew to become leaks before 60 years also appear in the table1.

Table2 summarizes results on a weld-by-weld (trial-by-trial) basis. The number of individual cracks involved is net given, but only the sum of the surface lengths.

Table 1. Example of crack-Linking Information Printed out in pc-Praise at Time60 Years

```
At time (yrs)   60.00

    .00< a/h <=   .30

 % circumf.   [ ALL ]|[  1  ][  2  ][  3  ][  4  ][  5  ]

     .0- 20.0   28924|   28923      1      0      0      0
   20.0- 40.0       0|       0      0      0      0      0

    .30< a/h <=   .60

 % circumf.   [ ALL ]|[  1  ][  2  ][  3  ][  4  ][  5  ]

     .0- 20.0     361|     360      1      0      0      0
   20.0- 40.0       0|       0      0      0      0      0

    .60< a/h <=   .80

 % circumf.   [ ALL ]|[  1  ][  2  ][  3  ][  4  ][  5  ]

     .0- 20.0      26|      26      0      0      0      0
   20.0- 40.0       0|       0      0      0      0      0

    .80< a/h <=   .95

 % circumf.   [ ALL ]|[  1  ][  2  ][  3  ][  4  ][  5  ]
     .0- 20.0      10|      10      0      0      0      0
   20.0- 40.0       0|       0      0      0      0      0

    .95< a/h <= 99.00

 % circumf.   [ ALL ]|[  1  ][  2  ][  3  ][  4  ][  5  ]

     .0- 20.0      13|      13      0      0      0      0
   20.0- 40.0       1|       1      0      0      0      0
```

Table 2. Crack Size data sorted on a Weld by Weld basis 60 Years

	>0	>0.3h	>0.6h	>0.8h	>.95h
0 - 20%	28945	410	49	23	13
20-40%	1	1	1	1	1

8. Conclusions

A probabilistic fracture mechanics model of structural reliability is summarized that considers cracks to be two-dimensional such as semi-elliptical surface cracks. The model uses a fatigue initiate crack and crack growth model to grow initiating, semi-elliptical, fabrication defects. Critical flaw sizes for pipe breaks are based on a net section collapse criteria of fracture. Numerical results obtained for a weld in a large reactor pipe are then presented for randomly distributed material properties. As a conclusion, using the initiation only show a weakly cumulative probability of leak in the ferritic components, than it will be better to combine the effect of the initiation with a pre-existing crack.

9. References

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