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On Assessment of Initial Cracks for RI-ISI Analysis Purposes

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Abstract: The assessment of initial cracks for Risk Informed In-Service Inspection (RI-ISI) analyses of Nuclear Power Plant (NPP) piping systems is considered here. In RI-ISI analyses piping component specific risks are assessed based on estimated failure and consequence potentials, and typical analysed locations are welds. In general there exist two main approaches for assessment of piping failure potential in current relevant RI-ISI procedures: qualitative and quantitative. Here discussion concerning assessment of initial cracks connects primarily to the latter approach. Estimates of initial crack sizes are among the most influential input parameters in terms of RI-ISI analysis response. Of the quantitative analysis approaches structural reliability procedures can best capture the relative piping component failure potential/probability differences caused by component specific differences in physical characteristics, loading conditions and inspection histories. The foremost of these procedures for piping components is probabilistic fracture mechanics (PFM). The initial crack sizes are part of the needed input data in the PFM analyses. Two developed approaches to recursively calculate estimates for initial cracks are covered here. According to application results by decreasing the average size of initial cracks from 1.0 mm to 0.3 mm leads to approximately 100 times smaller yearly pipe component failure probabilities.

Key words: PFM, RI-ISI, inspections, POD, initial crack size.

1. Introduction

The improvements concerning the structural reliability procedures, PFM in particular, together with development of piping degradation databases, allow making more accurate and versatile quantitative piping failure probability analyses. In the PFM based quantitative piping failure probability analyses, usually considering piping component leaks and/or breaks, the initial crack sizes are an essential part of the needed input data. As the variation of initial crack sizes is typically large, i.e. their scatter is remarkable, it is important to take this into account, which is best achieved by considering them as probabilistically distributed. In practise this can be carried out by constructing probabilistic density distributions (PDFs) separately for both initial crack depths and lengths.

For quantitative RI-ISI analyses the preceding failure potential analyses are most often carried out with suitable PFM analysis tools. Representative examples of such tools include WinPRAISE (by Structural Integrity Associates Inc.) [1], ProSACC (by Det Norske Veritas, DNV) [2], PRO-LOCA (by U.S. Nuclear Regulatory Commission, USNRC) [3] and PIFRAP (by Brickstad and Zang), this code has also been developed further and presently its name is NURBIT [4, 5]. All these PFM tools contain PDFs for initial crack depth or length or for both, and the theoretical background is presented in the associated documentation, as referenced above. These PDFs mainly concern cracks initiating during service due to various relevant degradation mechanisms, most often stress corrosion cracking (SCC) and fatigue (in their various forms). As for manufacturing induced initial cracks, WinPRAISE and PRO-LOCA contain PDFs also for them. A notable example from literature is the manufacturing crack distributions for NPP piping

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components of stainless steel developed by Khaleel and Simonen [6].

The main purpose of this paper is to present two developed procedures for recursively constructing PDFs for the depth and length of initial cracks. Here only cracks initiating during plant operation are considered, thus distributions of existing manufacturing cracks are omitted. As for the degradation mechanisms causing the initial cracks to nucleate, here the emphasis is on SCC. It has been experienced that some austenitic stainless steels used in NPPs are susceptible to SCC under certain conditions. SCC is a localised non-ductile progressive failure mechanism that occurs only in case the following three conditions are fulfilled simultaneously [7]: Stress around the crack tip is tensile, environment is aggressive, and material is susceptible to SCC. Also, SCC is a delayed failure process. That is, cracks initiate and propagate at a slow rate until the stresses in the remaining ligament of metal exceed the fracture resistance. The sequence of events involved in the SCC process is usually divided into the following three stages [7]: crack initiation, steady state crack propagation, and final failure.

The presented procedures could also be applied, as such or as slightly modified, to assessment of PDFs for initial cracks caused by other degradation mechanisms NPP piping systems can be prone to, such as fatigue (in its various forms). Estimates of initial cracks are among the most influential input parameters in terms of RI-ISI analysis response, or arguably the most influential ones. The approaches and procedures presented in this paper have been developed over several years at VTT [8, 9].

2. Assessment of Probabilistic Distributions for Sizes of Initial Cracks

2.1 Overview

When degradation data of good quality is amply available, statistical estimates are the preferred degradation potential analysis approach. However, in case of NPP piping components, degradation data are almost invariably so scarce, that the sole use of statistical estimates would lead in most cases to unacceptably poor accuracy. The situation gets obviously considerably worse, when this already scarce piping degradation data are divided to subgroups according to physical characteristics, such as piping component geometry and material types, as there may result subgroups having only a few degradation occurrences, or none at all. The only probabilistic degradation analysis approach that is capable to consider all relevant physical characteristics of the NPP piping components is structural reliability procedures, the foremost of those being PFM. The structural reliability procedures contain also uncertainties, related e.g., to model scope/accuracy, so the resulting absolute failure probability values may require validation/verification of suitable level and scale. However, structural reliability procedures well or better capture in the relative differences of the failure probability results the effects caused by differences in physical characteristics, loading conditions and inspection histories between the analysed piping components.

2.2 Use of PFM as Such and Together with Other Approaches

PFM is strongly based on deterministic fracture mechanics (DFM) procedures. When applying DFM, typically a local crack like flaw with a sharp front in a structural component is considered. Such flaws considerably increase the stresses in their vicinity, as compared to nominal far-field stresses, and especially so immediately ahead of the crack front. In DFM analyses these locally high stress fields are typically depicted with stress intensity factor and J-integral values along the crack fronts. When associating these load parameters with a suitable crack growth equation, the operational life time of the analysed component can be assessed in terms of calculated crack growth. Typical considered failure modes are brittle fracture and ductile tearing. Of these the latter mode typically concerns NPP piping, which are mostly made of ductile austenitic stainless steels. PFM differs from DFM by considering one or more of the input variables to be random instead of having deterministic values. For example, initial crack size is typically one of the rarely well known variables. Rather than assuming a fixed given initial size, this parameter can be projected over a range of sizes with probabilities of occurrence and detection estimated for each size. Other variables with typically scattered nature include: formation frequency of initial cracks, certain material properties, e.g., fracture toughness, tensile strength, and service conditions, e.g., frequencies of load cycles [10].

The advantage of PFM is the possibility of modelling clearly the uncertainties related to the material degradation process, and thus being also able to perform sensitivity analyses for the factors affecting this process. For ageing management purposes it is of interest, for example, to evaluate how changes in operating conditions can affect the failure probability of the structure [11].

However, PFM and/or other structural reliability procedures do not alone suffice for the quantitative assessment of degradation potential. The considered supporting methods here are statistical estimates and expert judgement. A notable example of combining structural reliability procedures with statistical estimates and expert judgement for assessment of piping component degradation potential is as follows [12]:

(1) Use of structural reliability procedures, where they exist, to provide good estimates of the relative differences in the failure probabilities;

(2) Statistical estimates based on both plant specific and global databases in order to provide anchoring points for both the structural reliability procedure based analyses and expert judgments;

(3) Use of formal expert judgements using a combination of deterministic structural models and design insight.

The results from the PFM analyses are in turn used for assessment of piping component degradation states, e.g., in terms of crack depth through pipe weld. When assessing piping component failure potential the effects of inspections are to be considered as well, which are usually included in the form of probability of detection (POD) functions. The quantitative estimates of piping component failure potential are typically expressed as probability of leak/break.

Typically the relevant needed initial crack estimates are, in addition to the above mentioned initial crack sizes, their initiation frequencies. These latter estimates obviously do not concern fabrication cracks. These estimates are dependent of pipe size, material, loads and process conditions as well as of the considered degradation mechanism. In practise it suffices to consider a few pipe size ranges (in terms of outer diameter and wall thickness) covering all considered sizes, as groups ferritic and austenitic steels, static and low/high-cycle mechanical and/or thermal loads and flow rate, and possibility for water chemistry and material carbon content to allow corrosion to occur. As for degradation mechanisms causing cracking, it often suffices to consider SCC and fatigue induced cracking in its various forms (i.e., due to low/high-cycle mechanical and/or thermal loads, thermal loads in mixing points, thermal loads in stratification locations). When applicable cracking data is scarce, which quite often is the case, coarser approach to the estimation of the scope/number of different probabilistic distributions must be resorted to. Utilisation of the most recent wide scope international crack databases, however, can potentially improve problems arising from the lack of crack data.

2.3 Overview of Two Developed Procedures for Recursively Constructing PDFs for the Depth and Length of Initial Cracks

Several approaches for recursive assessment of initial crack sizes can be schemed. Here the two developed approaches are briefly described.

The first approach, leaning more to expert judgement, is to obtain the available and applicable crack data, assemble them as a function of relative number of cases from smallest to largest crack sizes (considering either depth or length), select a reasonably realistic initial crack size mean value and lower by offset the size data values so that the cumulative 50% value equals the mentioned mean value and then fit a suitable probabilistic distribution function to thus treated data so that its integral over wall thickness equals one. This approach is based on the procedure presented in Ref. [5].

The second approach, being mainly based on PFM, also starts with obtaining the available and applicable crack data, and then assembling it as a function of relative number of cases from smallest to largest crack sizes (considering either depth or length). The next step is to select suitable fracture mechanics handbook equations or a fracture mechanics based analysis tool and applicable crack growth equation, and then calculate for a large enough number of crack sizes recursively the initial sizes, using as threshold criterion mode I stress intensity factor, K_I [MPa√m], value for SCC and K_I range, ΔK_I [MPa√m], value for fatigue induced cracking, both of which are obtained from fracture mechanics handbooks, and then fit a suitable probabilistic distribution function to thus treated data so that its integral over wall thickness equals one. When performing fracture mechanics based recursive computations, it must also be taken into account that the covered time span is not allowed to exceed the current time in operation. Typically crack growth equations for SCC are expressed as a function of time, whereas those for fatigue induced cracking as a function of load cycles, which in turn are composed of load transients that occur in time. The application of this approach is presented in Ref. [9].

2.4 Sources of Uncertainty in the Estimation of Initial Crack Dimensions

The estimation of size distributions for initial cracks is in several ways a challenging task, containing several sources of uncertainty.

As for crack data, these uncertainties relate to quality, amount, origin and type. Quality relates to correctness of diagnosing the degradation mechanism that caused cracking. Amount relates to problems associated with scarceness of available crack data. Origin relates to the applicability of crack data from other plants to the considered plant. Finally, type relates to the fact that existing crack data concerns only grown cracks, and thus the sizes of the initial cracks have to be somehow assessed recursively. Based on their uncertainty analyses Simonen and Khaleel conclude [13] that input data concerning initial crack distributions are the greatest source of uncertainty in calculations of failure probabilities.

The first initial crack size assessment approach relies quite heavily on expert judgement, which also causes uncertainty. The second approach contains uncertainties as well, e.g., the applied crack growth equations and their material and environment dependent model parameters are often somewhat conservative.

Despite the limitations and associated uncertainties of these two initial crack size assessment approaches, they are proposed to be used, as better ones do not currently appear to be available. However, great care must be taken when applying them. On the other hand, the failure probability assessment accuracy requirements in RI-ISI do not necessitate highly accurate physical modelling of the prevailing degradation mechanisms and loads concerning them, instead it suffices to achieve a reasonable accuracy scale, e.g., one decade in the failure probability exponent. There also remains work to do to both improve the accuracy of the estimates based on existing crack data as well as to further develop the procedures for recursive calculation of initial crack sizes.

2.5 Application of the Developed Fracture Mechanics Based Recursive Procedure to Assess PDFs for SCC Induced Initial Cracks

The approach and application to assess the probabilistic distributions of the sizes initial of SCC induced cracks from the data of detected cracks are presented in this section. Flaw data from nine Swedish boiling water reactor (BWR) units was used here for this purpose [5]. This data consists of detected and mostly circumferentially oriented cracks in the inner surfaces of piping components of austenitic stainless steel.

The steps of the fracture mechanics and statistical curve fitting based approach for assessment of the probabilistic distributions for initial sizes of SCC induced cracks are described in the following:

(1) Based on the applicable database cases concerning detected grown SCC induced circumferential inner surface piping cracks [5], the ages of these cracks are calculated.

(2) For recursive fracture mechanics SCC computations concerning the screened database crack cases the following input data are to be collected/prepared:

- Crack aspect ratio: crack depth divided by half of the crack length;
- Geometry data: pipe outer diameter and wall thickness;
- Material data: for the piping material of austenitic stainless steel, temperature dependent values of yield stress, ultimate stress, elastic modulus and coefficient of thermal expansion;
- Load data: primary membrane and bending stress values calculated with linear beam theory as corresponding to quasi-static operational conditions with pressure of 7.0 MPa and temperature of 286 °C, whose loads are considered to be typical for BWR NPP units [5];
- Welding process induced residual stresses in the welds; assumed according to SINTAP procedure [14].

(3) Performing recursive fracture mechanics SCC calculations concerning the screened database crack cases:

- Deterministic crack size decrease calculations keeping the aspect ratio case specifically as constant; calculations performed with fracture mechanics based analysis tool VTTBESIT, originally developed by the Fraunhofer Institut für Werkstoffmechanik (IWM), Germany, and further developed by VTT [8, 15];
- In the crack calculations the rate equation for crack depth against time, i.e. da/dt, was used, for equation background information [16];
- The values for temperature, material and environment dependent characterising parameters C and n were obtained from Ref. [17];
- Crack size decrease calculations backwards in time are performed for each crack case for as long as is the age of each case, which was taken to be from the time of detection to the start of operation of the NPP unit in question.

(4) Screening of the recursive fracture mechanics SCC calculation results to obtain the crack cases initiated by SCC:

- Here it is assumed that SCC has taken effect from the start of operation and that all recursively calculated crack cases that are in a fracture mechanics sense small then, i.e., below a few hundred μm in size, were taken as nucleated by SCC (from impurities, inclusions, small pores), while all other crack cases were taken as manufacturing flaws which have grown in size due to SCC;
- The threshold for crack initiation was assessed in terms of K_I against crack growth rate so that it is approximately such K_I value in the crack calculation results when the crack growth rate ceases to be dependent on K_I, for details concerning the assessment of K_I threshold values for initial cracks caused by SCC [18];
- As a result, those crack cases are obtained that are assumed to be caused by SCC, together with their assessed initial dimensions and times of nucleation.

(5) The estimated initial SCC crack dimensions were divided to subgroups of certain constant sizes:

- Initial crack depth relative to wall thickness; subgroup size of 5%;
- Initial crack length relative to inner pipe

circumference; subgroup size of 1%.

(6) The number of cases in each subgroup was calculated separately for assessed initial crack depths and lengths;

(7) The single value probability of each initial crack depth and length subgroup obtained from step 5 was taken as the number of cases in each subgroup, as obtained from step 6, divided by the number of all cases;

(8) The distributed probability of each initial crack depth and length subgroup was taken as dividing the single value probabilities obtained from step 7 by the subgroup width;

(9) The exponential function was selected as the form of probabilistic density function for both the estimated initial crack depths and lengths. The justifications for this are the following:

- Due to the nonlinear descending slopes of the estimated distributions of initial crack depths and lengths the best fit to them was achieved with the exponential function;
- The use of exponential function for estimates of initial crack dimension distributions is also recommended in the related relevant literature [19].

(10) In addition to fitting criteria, the quality of the obtained exponential probabilistic distributions was also confirmed through fulfilling the condition that the areas limited from above by each of the two probabilistic density curves, and from left and below by the coordinate axes, equal quite accurately to one.

The fitted exponential probabilistic density functions for estimated SCC induced initial crack depths and lengths are presented as probability against relative crack dimension in Eqs. (1) and (2), respectively:

$$f(x) = 0.251 \cdot \exp(-0.078 \cdot x) \tag{1}$$

$$f(x) = 0.388 \cdot \exp(-0.329 \cdot x) \tag{2}$$

where f is probability and x is relative initial crack depth or length expressed in %. As for the relative initial crack dimensions, concerning depth it is normalised against wall thickness, and concerning length against inner pipe circumference. Note that for relative initial crack depths from 0% to 15% the probability is set to zero, as well as for relative initial crack lengths from 0% to 0.5%.

The fitted exponential probabilistic density functions for estimated SCC induced initial crack dimensions were used further in the crack growth simulations so that the values are taken at random from the distributions, and then converted case specifically to physical dimensions, i.e., units of mm.

It was beyond the scope of this study to attempt to create such probabilistic distributions for the initial sizes of SCC induced initial cracks that could be recommended to be used for practical applications in larger scale. Instead the purpose here was more to demonstrate the applied approach and point out the sources of uncertainty/inaccuracy.

3. Application Example Concerning Failure Probability Analysis of NPP Piping Components

3.1 Analysed Piping Components and Associated Analysis Input Data

Here five piping components from an earlier study by mainly the same authors [20], were selected for PFM reanalyses. More precisely, it is the circumferential welds of these piping components that are and were analysed. The compared feature is the impact of different probabilistic distributions for initial crack sizes caused by SCC on rupture probability results. All reanalysed five piping welds are from the Shut-down cooling system of a Finnish BWR unit and located outside the containment in the reactor building. The base material of the considered piping components is austenitic stainless steel 376 TP 304. The material data of the base material [21], was mainly used for the examined welds as well. The dimensions of the examined piping components were taken from the respective design drawings. Values for the material, temperature and environment specific parameters C and n used in the associated crack growth rate equation were taken from Ref. [17]. The stress distributions over the walls of the considered piping components were calculated with beam theory, and the welding process induced residual stress were taken according to Ref. [22], as they were assumed according to this reference also in the mentioned earlier study [20]. The PFM analyses were carried out with probabilistic version of VTTBESIT [8, 15]. A summary of the input data needed in the pipe failure probability analyses is presented in Table 1 in the following.

3.2 Quantitative Piping Component Failure Probability Analyses

Here PFM simulations were used together with discrete Markov process based application to obtain the sought piping component failure probabilities, which here correspond to pipe weld breaks. This procedure was used both in the earlier study [20] and in the present background study [9], and is documented in more detail in these two reports. Thus only a brief summary of the procedure is presented here.

In the discrete Markov process application PFM simulations are used to construct the degradation matrices, M_d, for each analysed piping weld. Elements of M_d are $p_{i,j}$, where $p_{i,j}$ is the probability of transition from state i to j during each year. With a constant M_d (with respect to time), the PFM simulations can be treated in time independent fashion. The analyses cover the whole of the assumed operational plant life time, here taken as 60 years, and the piping component failure probabilities are calculated yearly, corresponding to yearly plant outages (i.e., times when the inspections of piping components are performed and possibly needed repairs/replacements are carried out). In the Markov process based analyses degrading of the analysed piping components is depicted in the form of degradation states, which cover all possible states that a piping component can be in, from intact to failure (break here). The used degradation states are defined as a function of crack depth and are described in more detail in Table 2.

Transition probabilities from one state to the others are computed by dividing the number of transitions to target state by the number of years spent in the source state:

$$p(i \to j) = \frac{N_{i\to j}}{N_i} \tag{3}$$

where $N_{i\to j}$ is the number of transitions from state i to j, and N_i is the number of years spent in state i. Since the system is assumed to be time homogenous, a single matrix is used for the whole of considered 60 years of operational plant life time. This means that all the years from 1 to 60 in the simulation are equal in weight. It follows that the whole simulation data of several thousands analysis runs covering 60 years can be used as a single plant operating year data source.

Inspections are modelled with the inspection matrix, M_i, in the Markov process. Elements of the inspection matrix M_i are the transition probabilities corresponding

Table 1 Summary of the input data needed in the pipe failure probability reanalyses of the five considered circumferential piping welds. All material property data are given at temperature of 286 °C.

Dimension & material property data		Loads & stress data	
Range of outer diameters (mm)	168 – 273	Pressure (MPa)	7.0
Range of wall thicknesses (mm)	14 – 21	Temperature (°C)	286
Yield strength (MPa)	125	Range of membrane stresses (MPa)	17-20
Tensile strength (MPa)	383	Range of bending stresses (MPa)	5-15
Fracture toughness (MPa√m)	350	Range of welding process induced residual stresses (MPa), assumed according to SINTAP procedure, and being tensional in the inner surface reaching with linear variation through pipe weld corresponding values of compression in the outer surface	85-156
Poisson’s coefficient [-]	0.3		
SCC rate equation; da/dt = C*(K_I^n) parameters;			
C [(mm/year)/((MPa√m)^n)]	1.42×10^{-4}		
n [-]	3.0		

to detection and repair/replacement of cracks. It is assumed in this method that all found cracks are repaired; a limitation is due to the lack of memory property in the Markov process. The used transition probabilities are defined as a function of crack depth and are described in more detail in Table 2.

3.3 Piping Component Failure Probability Analysis Results

The pipe component rupture probability analysis results for the considered five piping welds are presented and discussed in the following.

Each weld is at a flawless state in the analyses here when the operation of the NPP is started - year 0 in this study. When the NPP is operated, the yearly rupture probabilities start to climb towards a steady state rupture probability. This means that as the time advances, the significance of the initial state slowly decreases.

As mentioned earlier, the only considered degradation mechanism is SCC, and the sizes of the initial cracks are taken at random from the probabilistic distributions developed here for the SCC induced initial cracks. The effect of these for the pipe rupture probabilities are compared to the respective results calculated with corresponding more crude probabilistic distributions developed in the earlier study [20].

When considering piping component/weld specific failure probabilities, in the quantitative RI-ISI analyses they are used together with consequence measures, typically conditional core damage probability (CCDP) or conditional large release probability (CLRP) values which both are taken from the plant specific probabilistic safety assessment (PSA) analysis, to calculate piping component/weld specific risks, which can then be combined to obtain piping segment and system specific risks.

As an example, the pipe component rupture probability analysis results concerning one of the analysed five piping welds are presented in Fig. 1. It can be seen from Fig. 1 that depending on the weld the assumed operational plant life time of 60 years is enough for the welds to approximately reach steady state. The measure used for pipe degradation in this study is the average yearly rupture probability. The effects of the inspections are seen as saw-type deviations in the yearly rupture probability. Using this measure the rupture probability decreasing effects of the inspections are clear.

All in all the yearly rupture probability results are mostly quite similar for the five analysed piping weld cross-sections. This is an expected outcome, as SCC was the considered degradation mechanism in all cases and the loads as well as the overall conditions the covered welds are exposed to are very similar.

In this study the purpose is also to compare the effect of the two sets of probabilistic distributions for initial sizes of SCC induced cracks during operation to the pipe rupture probabilities. These probabilistic initial crack sizes are according to the new distributions developed in this study considerably smaller than those according to the earlier study [20]. For instance for the former distributions the mean crack depth is approximately 300 μm, whereas for the latter ones

Table 2 The used Markov process degradation states and transition probabilities are defined as a function of crack depth.

Markov state	0	1	2	3	4	5
a (mm)	I	0-1	1%-50% of WT	50%-99% of WT	99%-100% of WT	F
State description	New pipe components	Small flaw; very unlikely to detect	Grown crack; possibility of detection but no repair	Grown crack; possibility of detection with ensuing repair	Leak-before-break; repaired if detected.	Rupture
POD	NA	0.0	0.0	0.9	0.9	NA

Meanings of used abbreviations: POD is probability of detection, *a* is crack depth, I is intact state, F is failure state, WT is wall thickness, and NA is not applicable.

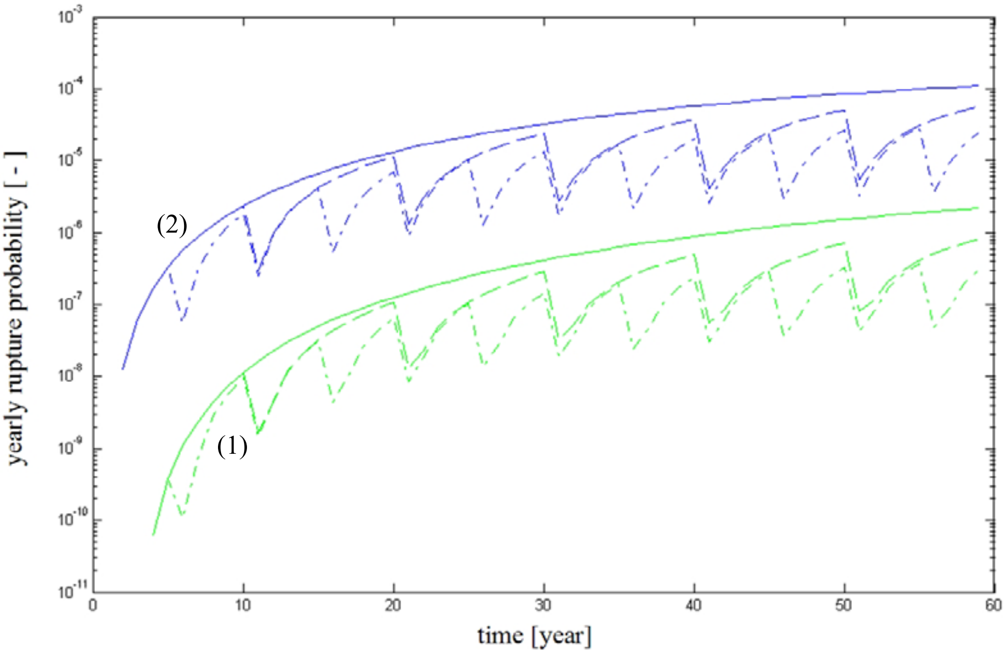

Fig. 1 The yearly rupture probability analysis results for piping weld, with outer diameter of 219 mm and wall thickness of 18 mm, as a function of operational lifetime.

(1) Green colour:results obtained with new developed probabilistic size distributions for SCC induced initial cracks, (2) blue colour: results obtained with earlier developed probabilistic size distributions for SCC induced initial cracks, continuous line; no inspections, dashed line; 10 year inspection intervals, dash-dotted line; 5 year inspection intervals.

approximately 1,000 μm, respectively. This is consequently reflected in the resulting yearly pipe rupture probabilities, as with the former distributions they are for most of the duration of the assumed operational plant lifetime approximately 100 times smaller than with the latter ones. This is a quite large difference, and indicates that the selection of the probabilistic distributions for initial sizes of SCC induced cracks during operation has a great impact on the consequent yearly pipe rupture probability results, an aspect which is useful to keep in mind e.g., when attempting to avoid unnecessary conservatism in the PFM and RI-ISI analyses. Concerning all cases and both input data sets, the yearly pipe rupture probability results vary approximately between 10^{-10} to 10^{-4}. The accuracy of the rupture probability results summarised here is considered to be at least reasonable. When comparing against other notable PFM based piping degradation analysis codes, in the latest version of PRO-LOCA [3] for cracks nucleated by primary water SCC (PWSCC) or fatigue it is assumed that their initial depth is 3.0 mm. Whereas in case of PIFRAP code [5] the initial depth of cracks nucleated by SCC is assumed as 1.0 mm.

4. Summary and Conclusions

The assessment of initial cracks for RI-ISI analyses of NPP piping systems is considered in this article. These estimates are needed in the quantitative piping failure potential assessment, and more specifically in the PFM based crack growth simulations. Two approaches to recursively assess sizes for initial cracks are presented; the first and simpler one is more leaning on expert judgement selection of initial crack mean size based on available and applicable crack data, whereas the second one is mainly based on calculating recursively for these data the initial crack sizes using fracture mechanics procedures. The limitations and uncertainties associated with these two approaches are also discussed, as well as the ways to improve their accuracy. Estimates of initial cracks are arguably the most influential input parameters in terms of model response. Through uncertainty analyses it has also been concluded that distributions for initial crack sizes are the greatest source of uncertainty in calculations of failure probabilities. However, the failure probability assessment accuracy requirements in RI-ISI do not necessitate highly accurate physical modelling of the prevailing degradation mechanisms and associated loads, instead it suffices to achieve a reasonable accuracy scale, e.g., of one decade in the failure probability exponent. So, despite of the limitations and uncertainties associated with these two initial crack size assessment approaches, they are proposed to be used, as better ones do not currently appear to be available. However, great care must be taken when applying them. The initial crack size distribution approach that is based on fracture mechanics procedures is considered to give more realistic results than the other approach that is more based on expert judgement.

In the light of the obtained analysis results the effect of the initial crack sizes to the failure probability analysis results is remarkable. For instance, with the new developed initial crack size distributions with the mean crack depth of approximately 300 μm as compared to earlier developed ones with the mean crack depth of approximately 1,000 μm, the yearly pipe rupture probability result values obtained from the Markov application analyses are for most of the duration of the assumed operational plant life time approximately 100 times smaller. When comparing against other notable PFM based piping degradation analysis codes, in the latest version of PRO-LOCA [3] for cracks nucleated by PWSCC or fatigue it is assumed that the initial depth is 3.0 mm. Whereas for PIFRAP [5] the initial depth of cracks nucleated by SCC is assumed as 1.0 mm.

The scope of crack data in the international NPP piping component degradation databases has increased and quality improved, respectively, which consequently allows improving accuracy of the statistical piping degradation estimates. An example of such databases is OPDE (OECD Piping Failure Data Exchange), which is an advanced good quality piping failure database containing crack data from twelve countries operating NPPs [23, 24]. However, the piping degradation databases do not yet contain piping component and weld population data. Thus such data are to be acquired case specifically, i.e., from the considered plant. Only when having the population data as well it is possible to make degradation mechanism specific estimates of the frequency of crack initiation. In this connection it could be considered to use plant specific crack data, if having such available, to adjust to some extent the estimates of initial cracks based on worldwide database data.

The possibilities to develop the first of the above depicted approaches for recursive assessment of initial crack sizes are somewhat limited. As this procedure is mainly based on lowering the assembled crack size data values by offset so that the cumulative 50% value corresponds to initial crack mean size estimate as selected by expert panel, any worthwhile model development can practically only focus on improving the technical basis and accuracy of this estimate. However, the simplicity of the procedure in question is also its virtue, as it is easy and quick to use, so procedure development could very well prove to be valuable.

The possibilities to develop the second of the above depicted approaches for recursive assessment of initial crack sizes are wider, as well as perhaps more challenging. As mentioned above, the commonly used crack growth rate equations together with their environment dependent model parameters are to some extent conservative. Often these model parameters are defined so that the resulting crack growth rate curve envelops the underlying crack data. As probabilistic approaches attempt to consider the analysed phenomena more as they are in reality, the existing crack growth rate equations and their environment dependent model parameters should be modified accordingly, e.g., to correspond to the best estimates of the respective/associated crack data. Also the threshold values for K_I and ΔK_I could be improved, which would require a data survey concerning applicable databases. Methods to define the mentioned threshold values using available crack data are described in fracture mechanics handbooks, e.g., Ref. [18]. Also the effect of such phenomena as crack closure e.g. in compressive stress fields and overloads to crack growth rate should be considered. Another issue needing a closer look is welding process induced residual stress distributions. These are typically defined quite conservatively, e.g., ASME recommendations, API 579 procedure, R6 Method, Revision 4, SINTAP procedure and FITNET procedure, so that the residual stress distributions are tensile side upper bound assumptions with regard to the underlying stress data. For probabilistic analysis purposes the existing weld residual stress assumptions should be modified to correspond to e.g., best estimates of the underlying stress data.

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