Benchmarking of structural reliability models for risk analyses of piping

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Abstract:
In the last two decades the regulatory "risk informed" approach for nuclear power plants started to develop in the USA. Shortly after that, this approach was emerging in several European countries. The idea in a risk informed in service inspection (RI-ISI) process is to evaluate the failure potential or rate in passive systems, structures and components. In a quantitative RI-ISI process the failure probability or rate at each location is usually calculated with so called Structural Reliability Models (SRMs). This paper shows the results of a benchmark study with five different SRMs conducted in the frame of the European project NURBIM (Nuclear Risk Based Inspection Methodology for Passive Components). The SRM codes are demonstrated to work in a wide range of parameter variations and differences in the calculated failure probabilities can in most cases be explained from the theoretical basis of the SRMs. A set of requirements to be fulfilled by a SRM and the associated software for application in a risk informed in service inspection study are then formulated.

1 INTRODUCTION

In the past, priority has been given to deterministic approaches for the assessment of the safety of reactor pressure vessels, containments, piping and other passive structures in nuclear power plants. In several technical fields, as e. g. civil engineering, steel construction, offshore constructions, the national and international rules and regulations are increasingly oriented towards the quantitative determination of structure reliabilities. This also applies to the field of nuclear technology where various international rules and regulations go over to define quantitative specifications for the reliability of main components. The regulatory "risk informed" approach for nuclear power plants started to develop in the USA in the mid nineties. Shortly after that, this approach was emerging in several European countries.

The idea in a risk informed in service inspection (RI-ISI) process is to evaluate the failure potential or rate in passive systems, structures and components to provide a quantitative or qualitative measure of the associated risk. Within this context, risk is defined in terms of consequences from Probabilistic Safety Analyses (PSA), i.e. the Conditional Core Damage Probability or Conditional Large Early Release Probability, times the failure frequency of incurring these consequences. The outcome is a risk ranking of individual locations. After that the locations to be inspected, the frequency and type of inspection are selected and the change in risk after applying this inspection programme is evaluated. The main objective of the process is to obtain a programme for inspection which addresses the main risk significant areas with a sufficient risk reduction and at the same time may optimize the resources necessary for the inspection programme. **Fig. 1** illustrates the major elements of a RI-ISI programme.

Structure of a RI-ISI Programme

Major elements of a RI-ISI programme

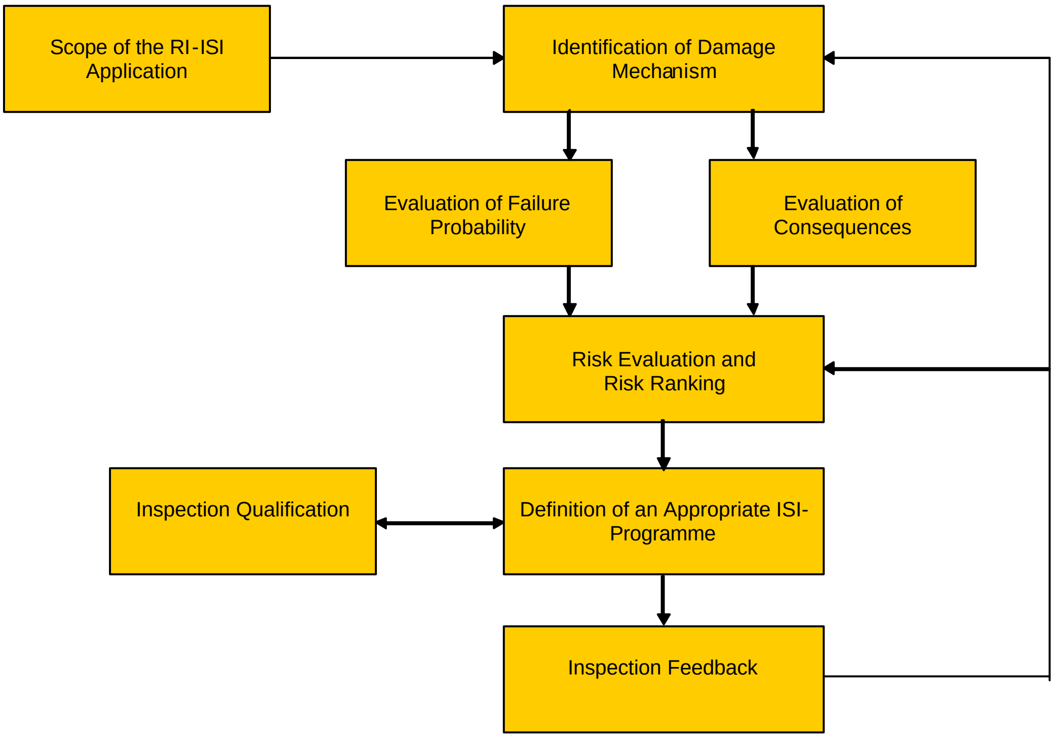

Fig. 1: Major elements of a Risk Informed-In Service Inspection programme

In a quantitative RI-ISI process the failure probability or failure frequency at each location is usually calculated with SRMs. These models are usually based on facture mechanics principles when the damages occur as crack mechanisms. The probability of failure due to a specific damage mechanism is calculated from the input data such as the component geometry, the material data, the expected loading history, the defect geometry, the damage progression and the assumed detection efficiency of the in service inspection. The probabilistic nature of the result is determined by the uncertainties of the input data entering the deterministic routines.

This paper presents the results of a benchmark study with different SRMs conducted in the frame of the European project NURBIM (Nuclear Risk Based Inspection Methodology for Passive Components) [1].

2 BENCHMARK STUDY

One objective of NURBIM was the investigation of the accuracy of reliability methodologies for passive components. Therefore different approaches of determining the reliability of piping systems were tested and compared with regard to their capabilities and efficiency for specific problems. One of the major topics of this project was named “Review and Benchmarking of Structural Reliability Models (SRMs) and associated software”. The benchmark study was performed for two damage mechanisms starting from pre-existing cracks, stress corrosion cracking (SCC) and fatigue.

The following five SRM codes are considered in the benchmark study:

- WinPRAISE, Engineering Mechanics Technology software for fatigue or SCC in nuclear piping components [2].
- NURBIT, DNV software for RI-ISI for SCC or pre-existing cracks in nuclear piping components [3].
- ProSACC, DNV software for SCC or fatigue or pre-existing cracks (non-growing defects) in general components [4].
- PRODIGAL, Rolls-Royce software for fatigue or pre-existing cracks in different components [5].
- PROST, GRS software for fatigue in cylindrical shaped components [6].

2.1 Benchmark Study Definitions

The benchmark analyses are performed by first defining a baseline case and then varying each parameter one by one, keeping all other parameters fixed at their baseline values. The baseline case corresponds to the "best estimate" values of all parameters, reflecting actual plant conditions for a Large, Medium and Small diameter pipe. **Table 1** summarizes the pipe dimensions used for both studies. The cumulative rupture probability and the cumulative leak probability after 40 years from pre-existing circumferential cracks in girth welds are evaluated for SCC and fatigue, respectively.

Pipe dimensions	Fatigue	SCC
Small diameter in a stainless steel pipe	D = 88.9 mm t = 11.1 mm N = 6	D = 168 mm t = 12.5 mm N = 10
Medium diameter in a stainless steel pipe	D = 324 mm t = 33.3 mm N = 20	
Large diameter in a stainless steel pipe	D = 861 mm t = 62.2 mm N = 64	D = 680 mm t = 40 mm N = 36

Table 1: Pipe dimensions considered (D = Outer pipe diameter, t = wall thickness, N = Number of welding passes SMAW or SAW).

The following parameters are varied in the sensitivity analyses:
1) Initial crack depth.
2) Aspect ratio or crack length.
3) Flow stress.
4) Yield stress and ultimate tensile strength (only for fatigue).
5) Fracture toughness.
6) Dead weight stress (only for SCC).
7) Secondary stress.
8) Upset stress (Design limiting stress).
9) Vibration stress (threshold effects, only for SCC).
10) Weld residual stresses (only for SCC).
11) Crack growth rate.
12) Number of cycles (only for fatigue).
13) Leak rate detection limit (only for SCC).
14) ISI, effectiveness in terms of probability of detection (POD) for a fixed inspection interval.
15) ISI, inspection interval.

Depending on the damage mechanism and the SRM code used, some of the parameters were treated as random and some parameters were treated deterministically in the benchmark study. In this paper selected results are presented only. The complete study is reported in [7] for SCC and in [8] for fatigue.

2.2 Selected results of SCC benchmark

Table 2 shows the results for the (small) leak and rupture probability after 40 years for the baseline case and using NURBIT Version 2.0, [3] and WinPRAISE Version 4.24, [2].
It is observed from Table 2 that the small diameter pipe gives higher rupture probabilities than the large diameter pipe. This is mainly due to the thicker pipe giving longer times to failure (more favourable stress state) and also larger leak flow rates which are easier to detect.

Pipe dimension	**NURBIT** small leak	**NURBIT** rupture	**Win-PRAISE** small leak	**Win-PRAISE** rupture
Small pipe	2 E-2	1 E-4	9 E-5	6 E-5
Large pipe	7 E-3	2 E-5	2 E-5	1 E-5

Table 2: SCC baseline failure probabilities after 40 years.

Furthermore, NURBIT gives slightly larger rupture probability values than WinPRAISE for the similar problem. The reason for this is due to the different theories of failure probability which NURBIT and WinPRAISE represent in some aspects. In NURBIT, contribution to the rupture probability is obtained only if all the following conditions are fulfilled:

a) a stress corrosion crack has been initiated.

b) the initial crack size, pipe stresses and crack growth rates are such that rupture is predicted to occur before end of operation (40 years).

c) the crack remains undetected with inspections.

d) the through-wall crack (which has been grown from a surface crack) remains undetected with leak flow rate detection.

Since a) and c) are assumed a priory for the baseline case, differences in rupture probability for NURBIT in this case originates from not all initial crack lengths fulfilling condition b) above and from different leak flow rate evaluations. A higher leak flow rate is easier to detect and will result in a lower rupture probability through the probabilistic leak flow rate detection model in NURBIT. For the large diameter baseline case in NURBIT, rupture is predicted to occur immediately after wall penetration for initial crack lengths longer than about 71% of the inner circumference. This corresponds to the no LBB (Leak Before Break) situation and for those cracks there is no benefit from leak flow rate detection. For the small diameter pipe baseline case in NURBIT, LBB is predicted for all initial crack length up to a full circumferential initial crack. However, for very large initial crack lengths the leak flow rate just before rupture is quite small and thus little benefit is coming from leak flow rate detection for such long cracks. The reason for this is that critical conditions is reached quite soon after wall penetration for these long initial crack lengths and the much smaller crack length at the outside of the pipe at wall penetration does not have time enough to grow much before critical conditions (rupture) is reached.
The WinPRAISE definition of a rupture is when the surface crack becomes unstable with the subsequent through-wall crack also being unstable. The surface crack may also lead to a stable leak and after which the growth of the through-wall crack eventually leads to rupture with no leak detection before rupture.

It is also interesting to note the differences in the (small) leak probabilities between NURBIT and WinPRAISE in **Table 2**. This is the probability of a wall penetration integrated over all assumed initial crack sizes, regardless of the leak flow rate at wall penetration. However, often this initial leak flow rate is quite small and therefore this is here denoted the small leak probability. Since the conditions a) to c) are fulfilled for all initial crack sizes for the small diameter pipe in NURBIT, the small leak probability will approach 3 E-2, which is the crack existence frequency or the number of pre-existing cracks per weld. (The condition d) is only relevant for rupture.) For the large diameter pipe in NURBIT, the small leak probability will not tend to the crack existence frequency. This is because for the smallest initial crack lengths, a leak (and rupture) is not predicted to occur until after 40 years which means that for these small initial crack lengths, there will be no contribution to the small leak probability. In general, the rupture probabilities are smaller than the small leak probabilities in NURBIT due to the benefit of leak flow rate detection as discussed above.

However, the WinPRAISE results in **Table 2** show that the small leak probability is not very different from the rupture probability after 40 years. This is because almost all initial crack sizes in WinPRAISE will lead to rupture as soon they have grown through the pipe wall, i. e. a no-LBB situation for all sampled cracks for the baseline cases, provided they grow through the wall within 40 years of operation. Thus for the baseline cases, the WinPRAISE results will be less sensitive to the leak flow rate detection limit.

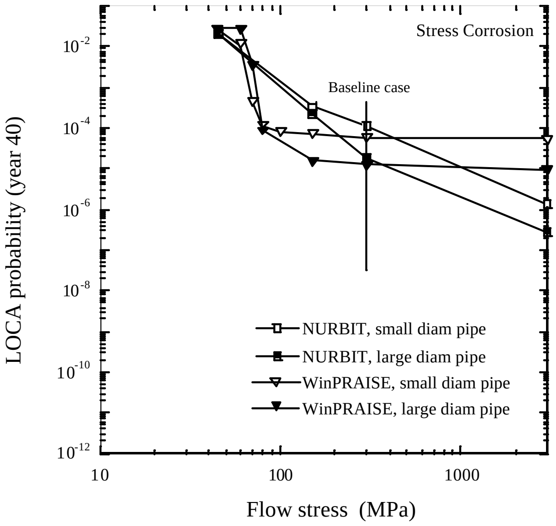

Fig. 2: Rupture probability by variation of flow stress for SCC

Fig. 2 shows the benchmark result for a variation of the flow stress. A vertical line indicates the baseline value, 300 MPa. **Fig. 2** demonstrates a smaller rupture probability for increasing flow stress. The NURBIT result for the large diameter pipe and a large flow stress shows that LBB is always predicted even for a very large initial crack length due to the increased critical through-wall crack size when a large flow stress is used. Thus benefit from leak flow rate detection is obtained for all initial crack lengths and this decreases the rupture probability. This is different from the baseline case where a baseline flow stress caused no LBB for long initial crack lengths which implies a substantial contribution from long initial crack lengths to the rupture probability. A similar behaviour is noted for the small diameter pipe using NURBIT. For the small diameter pipe, a higher flow stress will also lead to a longer critical through-wall crack size which increases the leak flow rate just before rupture. The increased leak flow rate is easier to detect and this decreases the rupture probability.

The WinPRAISE results show a relatively sharp transition from low to high rupture probabilities. This corresponds to the situation when the load-controlled stresses are approaching the flow stress. The load-controlled stresses are the sum of the stress from the internal pressure and the dead weight stress, which amounts to 48.4 MPa and 54.6 MPa for the small and large diameter pipe, respectively. As discussed in more detail in relation to **Fig. 4**, the leak flow rate detection will not make much difference for the WinPRAISE results in the baseline case. Almost all cracks will lead to rupture as soon as they have grown through the pipe wall, provided they grow through the wall within 40 years. This means that for WinPRAISE, the rupture probability at year 40 will be determined by the fraction of cracks that will lead to rupture which are essentially determined by the critical through wall crack length. If rupture is limited by net section collapse, then the critical through wall crack size is only weakly dependent on the flow stress for a flow stress larger than about 300 MPa. This is due to that the load-controlled stresses are much smaller than the flow stress, regardless if the flow stress is equal to 300 MPa or 3000 MPa. This explains the quite small influence from larger flow stresses for the WinPRAISE results.

Note that for the smallest value of the flow stress (equal to 45 MPa), all the rupture probabilities will approach more or less the similar value. For a sufficiently small flow stress (compared to the primary stresses), even an uncracked pipe will be predicted to break and then the rupture probability will be the occurrence frequency of IGSCC, i. e. the number of pre-existing cracks per weld (3 E-2).

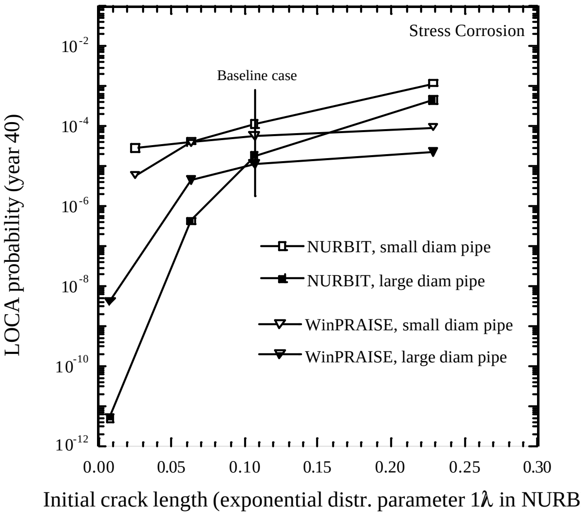

Fig. 3: Rupture probability by variation of initial crack length for SCC.

Fig. 3 shows the influence from the initial crack length. The rupture probability is plotted versus the exponential distribution parameter 1/λ for the NURBIT formulation of initial crack length. For the WinPRAISE results, this corresponds to a translation to an equivalent exponential distribution for the initial aspect ratio. The values of 1/λ for the initial crack length with NURBIT and the rate parameter λ for the initial aspect ratio with WinPRAISE are calibrated to coincide for the mean value of initial crack depth 2.56 mm.

It is observed from **Fig. 3** that the rupture probability decreases for shorter mean values of the initial crack length, both for NURBIT and WinPRAISE. This is explained by the fact that shorter initial crack lengths will result in longer times to rupture, more than 40 years for a sufficiently short initial crack length.

Especially for the large diameter pipe in NURBIT, the rupture probability after 40 years is very small for a short mean value of the initial crack length in **Fig. 3**. In this case, the longer initial crack lengths will not contribute much to the rupture probability due to the exponential decrease of the probability for existence of long initial crack lengths, even though a no-LBB situation is predicted. For the baseline case these longer cracks do contribute significantly to the rupture probability.

Fig. 4 shows the influence from the leak flow rate detection limit. It is observed from **Fig. 4** that the NURBIT results are quite sensitive to the leak flow rate detection limit. However, note that the considered leak flow rate detection limits cover a very wide range. Realistic leak flow rate detection limits would correspond to a range from 0.03 to 1 kg/s. For a very large detection limit, virtually no leak flow rates are

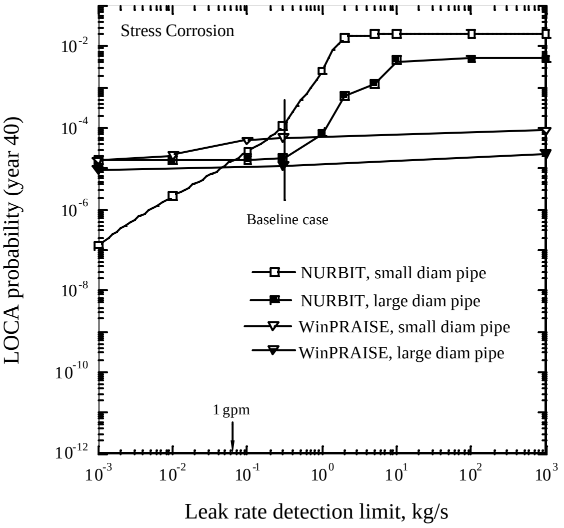

Fig. 4: Rupture probability by variation of leak rate detection limit for SCC.

ever detected before rupture and the influence of the detection limit is actually small above 2 kg/s for the small diameter pipe. This is due to that the leak flow rate just before rupture is less than 2 kg/s for all initial crack lengths for the small diameter pipe using NURBIT. The upper limit of the rupture probability for the small diameter pipe for a large leak rate detection limit is the crack existence frequency 0.027 cracks per weld. This value is reached because all initial crack sizes will contribute to rupture, the growth time is less than 40 years for all initial cracks and neither leak flow rate detection, nor inspections (since inspections are not included in the baseline case), will detect the cracks before rupture. On the other hand when specifying a very small leak flow rate detection limit, all leak flow rates will be detected, no matter how small they are. This means that the rupture probability will be quite small unless break occurs before leak. For the small diameter pipe, all initial crack lengths will lead to a leak before a rupture is predicted.

The WinPRAISE results show much less sensitivity from the leak flow rate detection limit. This is because almost all initial crack sizes will lead to rupture as soon they have grown through the pipe wall, i.e. a no-LBB situation for all sampled cracks, provided they grow through the wall within 40 years of operation. For the large diameter pipe with NURBIT the trend is similar but the upper limit of leak flow rate detection limit when the rupture probability saturates will be larger, reflecting the larger leak flow rates before rupture for the large diameter pipe. Also for very small leak flow rates the rupture probability saturates the large diameter pipe with NURBIT. For a smaller leak flow rate detection limit than the baseline value of 0.3 kg/s, the rupture probability will be virtually unchanged. This is due to that the results are dominated by the no-LBB results for long initial crack lengths. For the no-LBB cases, the leak flow rate detection limit will not influence the result at all.

Note that NURBIT is using complex crack shapes which is reflecting the observed experimental behaviour for cracks that have grown to through-wall cracks; the crack length at the outside of the pipe just after break-through is often much smaller than the crack length at the inside of the pipe, see **Fig. 5**. This affects the crack growth after wall penetration as well as the crack opening areas and leak flow rates. The difference in behaviour compared to the NURBIT results is partly due to the simplification in WinPRAISE that at wall penetration the entire length of the surface crack is assumed as the through-wall crack length. Another feature in WinPRAISE is the J-solution used to compute crack stability once the crack is through-wall. WinPRAISE uses a tension solution, which assumes the maximum stress is applied around the circumference. It does not consider bending (the circumferential variation of the stress). For a given maximum stress, a tension solution would result in a shorter crack for instability than a solution that considered bending. This conservative assumption promotes a non-LBB behaviour.

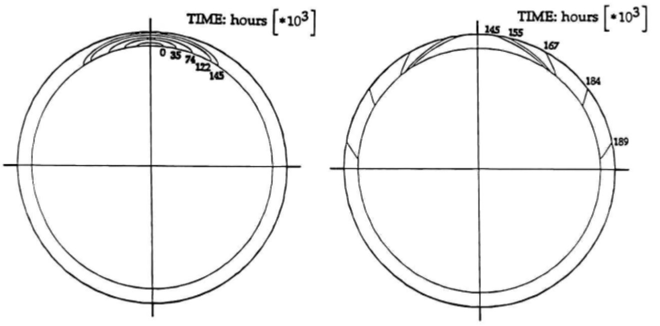

Fig. 5: Typical crack shape development in NURBIT.

The assumed initial crack length is also of key importance, see **Fig. 6**. In **Fig. 6** the WinPRAISE behaviour for the large diameter pipe is shown for specifying a different rate parameter λ for the aspect ratio. In the baseline case, $\lambda = 0.026$ is used which makes the assumptions of the initial crack lengths similar as with NURBIT. This corresponds to relatively long initial crack lengths, a mean value of about 10.6% of the inner pipe circumference, taken from damage statistics of IGSCC in Swedish BWR pipes. In **Fig. 6**, also $\lambda = 0.5$ is considered which means much shorter initial crack lengths. When using $\lambda = 0.5$, WinPRAISE will now also give a transition from small LOCA probabilities for small leak flow rate detection limits to larger LOCA probabilities for large leak flow rate detection limits.

When specifying a very low leak flow rate detection limit, all leakages will be detected (if not break is occurring immediately after wall penetration). When λ = 0.5, there will be many short cracks (in length) which will be detected before rupture by leak flow rate detection and this will cause a low rupture probability. (This is also indicated by a much larger leak probability, of about 1 E-7 in Win-PRAISE when the rupture probability is 1 E-10 for the lowest leak flow rate detection limit.) On the other hand, if the leak flow rate detection limit is large, no leak flow rates will be detected before rupture and this makes the rupture probability to be higher. In this case, for the highest leak flow rate detection limit, the leak probability in WinPRAISE will be the same as the rupture probability, about 1 E-6, which makes sense. This case corresponds to a situation when no credit for leak flow rate detection is made.

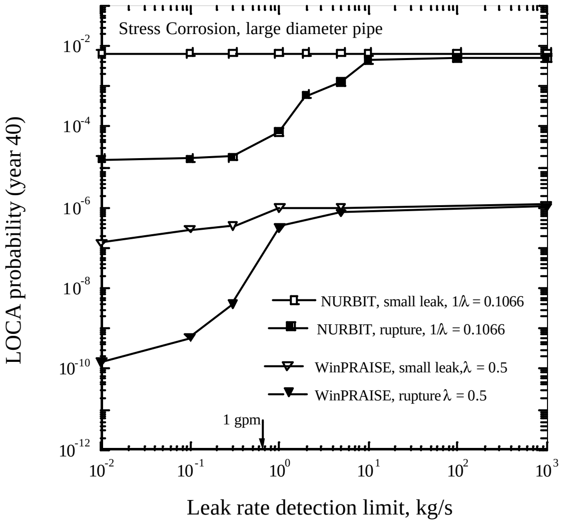

Fig. 6: Variation of leak rate detection limit for SCC using different initial crack length assumptions

The WinPRAISE results in **Fig. 6** regarding the influence from the leak flow rate detection limit on the small leak and rupture probability have also been confirmed for fatigue in the paper by Simonen et al [11]. **Fig. 6** highlights the importance of including leak rate detection in risk evaluations. If leak rate detection is ignored (corresponding to setting the leak detection limit to a large value), the risk of core damage can be severely overestimated which also may make it more difficult to select the high risk components from the population.

2.3 Observations from the SCC

1. The benchmark study for SCC has generated results for the accumulated rupture probability after 40 years using NURBIT and WinPRAISE, which in most cases are consistent with expectations, given the SRM theory assumptions of the respective code.

2. Both NURBIT and WinPRAISE have been demonstrated to result in a wide range of rupture probabilities when using extreme values of input parameters. These rupture probabilities cover very small values (1E-10) up to unity over the operating life of the component.

3. Differences between NURBIT and WinPRAISE exist and do influence the evaluation of the rupture probability. NURBIT is a relatively simple code with limited possibilities of treating variables as random. The differences regard the treatment of certain stresses (weld residual stress, thermal expansion stress, upset stress, vibration stress), the treatment of the initial flaw size, the crack shape development at wall penetration and for the sub-critical growth of the through-wall cracks and the treatment of leak flow rates and their detection. It is important that users of the codes are aware of these differences in order to correctly assess the importance of the sensitivity analyses and the use of the codes in real RI-ISI applications.

4. The main influencing parameters for the accumulated rupture probability after 40 years are for NURBIT the flow stress, initial crack length, leak rate detection limit, dead weight stress, vibration stress amplitude and crack growth rate. For WinPRAISE, the main

influencing parameters are the initial crack depth and length, dead weight stress and crack growth rate.

5. The deterministic comparison for through-wall cracks of NURBIT and WinPRAISE regarding the evaluation of J-integrals, crack opening areas COA and leak flow rates have generally resulted in small differences, see the full report by Brickstad [7]. Only NURBIT accounts for residual stresses for through-wall cracks. For the studied case, the effects of weld residual stresses for through-wall cracks are relatively small on COA and leak flow rates. However, they have a larger effect on J-integrals and the times to initial leak and to rupture.
6. In general, both NURBIT and WinPRAISE give a consistent ranking of the rupture probability between the small and large diameter pipe during the benchmark study. With a few exceptions, the rupture probability for the small diameter pipe is larger than for the large diameter pipe.

2.4 Selected results of fatigue benchmark

The accumulated leak probability after 40 years, P(40) and at year 0, P(0) for the baseline cases for all three pipe sizes are shown in **Tables 3 and 4**.

	Small Pipe	**Medium Pipe**	**Large Pipe**
WinPRAISE 4.31	5 E-06	2 E-05	2 E-06
PROST	4 E-06	3 E-05	7 E-06
ProSACC 0.92	3 E-06	1 E-05	8 E-07
PRODIGAL	2 E-05	3 E-05	3 E-05

Table 3: Fatigue, accumulated leak probabilities after 40 years.

	Small Pipe	**Medium Pipe**	**Large Pipe**
WinPRAISE 4.31	2 E-07	5 E-07	3 E-09
PROST	4 E-08	1 E-07	3 E-10
ProSACC 0.92	2 E-07	5 E-07	7 E-10
PRODIGAL	3 E-07	2 E-07	9 E-09

Table 4: Fatigue, accumulated leak probabilities at year 0.

It is observed that the leak probabilities after 40 years for all codes increase from small to medium pipe and then decreases from medium to large pipe. The trend is more or less significant. WinPRAISE and ProSACC exhibit the largest differences and PRODIGAL the smallest. The accumulated leak probabilities after 40 years are in a range of 8 E-7 to 3 E-5 with the biggest scatter for the large pipe. The cyclic stress range is of about 70 MPa for all three pipe sizes, but the pre-existing crack depth distributions are very different. The crack depth distribution for the small pipe includes more deep cracks normalized with the wall thickness compared to the flaws for the large pipe. However the higher stress intensity factors of the large pipe cracks due to the larger crack depths in absolute units lead to higher crack growth rates and compensate this effect in such a way that the failure probabilities for both pipes are of the same order. Furthermore it is remarkable that the results for the medium size pipe coincide very well. They differ by not more than a factor of 3, whereas the differences for the small and large pipe are by factors of 7 and 30 respectively.

The accumulated leak probability P(0) in PROST, ProSACC and WinPRAISE is calculated as the failure probability for applying the load of the first loading cycle. In PRODIGAL the load of the most severe loading cycle during the whole operating time is applied. All codes show the lowest failure probability for the large pipe due to the small number of deep cracks in the given distribution. The accumulated leak probabilities at the beginning of operation are in a range of 3 E-10 to 5 E-7, again with the biggest scatter for the large pipe. The scatter between the codes reflect the different failure estimation approaches and the different statistical methods like Monte-Carlo (WinPRAISE), first order Reliability method or Monte-Carlo (ProSACC), Monte-Carlo and stratification method (PROST), or direct integration (PRODIGAL).

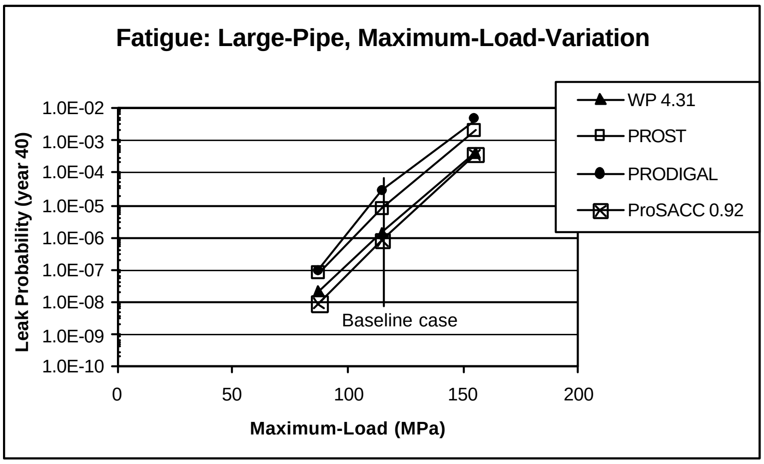

Fig. 7: Variation of maximum load for fatigue.

The loading cycle stress range of the baseline cases is of about 70 MPa. This stress range has been varied from 41 to 101 MPa for the small diameter pipe, from 35 to 105 MPa for the medium diameter pipe and from 42 to 109 MPa for the large diameter pipe. The variations are done by keeping the minimum stress constant and vary the maximum stress. **Fig. 7** shows the results for the large diameter pipe. A higher loading results in a higher stress intensity factor and therefore in a higher crack growth rate during the life time that should lead to a larger accumulated leak probability. All codes confirm this trend as shown in **Fig. 7**. The change in leak probability is about 4 orders of magnitude and this is among the largest change of all parameter variations.

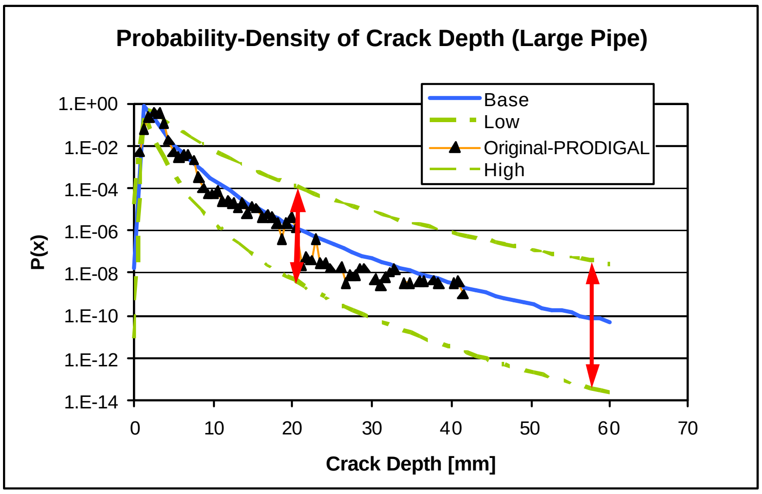

Fig. 8: Fatigue, used crack depth distributions for large pipe.

The prescribed variation of the crack depth distributions for the large pipe is shown in **Fig. 8**. The mean value of the lognormal distribution is changed while keeping the ratio of standard deviation to mean value constant. This results in a difference of the probability density of a few orders of magnitude for the deeper cracks, while the probability density of the short cracks in the first quarter exhibit a less significant change.

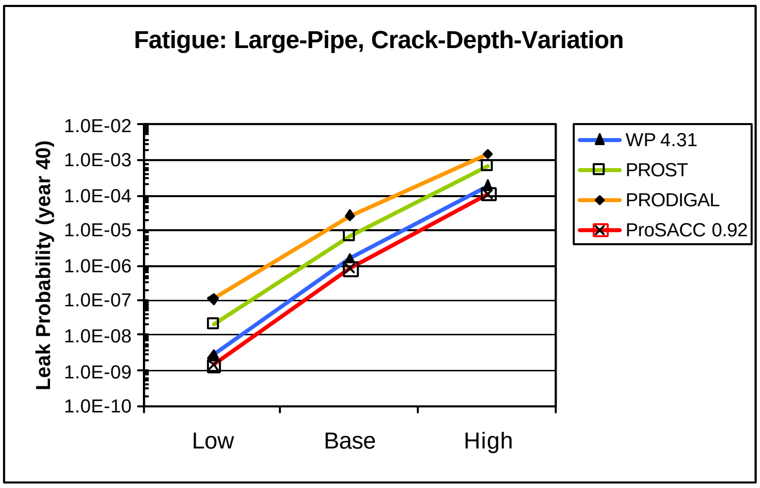

Fig. 9: Variation of crack depth distribution see Fig. 8 for fatigue.

The calculated accumulated leak probabilities after 40 years reflect the probability density change of the deep cracks. A change from low to high estimates of flaw densities results after 40 years in a difference of about 4 to 5 orders of magnitude independent of the code (see **Fig. 9**). All codes show the same trend. The scatter between the codes is of about 1 to 2 orders of magnitude. It is observed that the failure probability is mainly driven by the distribution of the deep cracks. Similar results are generated for the small and medium pipe.

The baseline cases were calculated without any inspection. In all calculations with inspections it was assumed that the first inspection always starts after 10 years of operation. In a first study the influence of 3 different inspection effectiveness was investigated, taken from Simonen and Woo [10]. These were named poor, good and advanced at the years 10, 15 20,…,35. **Fig. 10** shows the probability of detection as a function of the normalised crack depth. The results in **Fig. 11** show a good agreement between WinPRAISE and PROST. PRODIGAL shows a similar trend, but exhibits a stronger influence on the leak probability by changing the efficiency from poor to good. In a second study the influence of the inspection interval for a good inspection team has been investigated (see **Fig. 12**). From this investigation it is seen that the impact of the number of inspections for fatigue driven cracks is not very significant. The first inspection after 10 years detects most of the larger fabrication flaws, which are the dominant contributors to failure. Once these flaws are eliminated by the first inspection at 10 years, the subsequent inspections at 20 and 30 years provide little additional benefit, because the larger flaws have already been detected and repaired. The decrease in leak probability of subsequent inspections after a first 10 year inspection is not very strong, whereas the efficiency of the inspection is more important to an improvement. In our selected case a good inspection after ten years leads to a lower accumulated leak probability at the end of plant life than a poor inspection every 5th year starting at year 10.

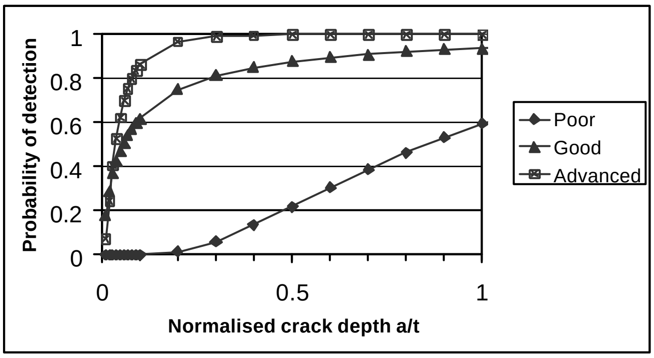

Fig. 10: Probability of detection used in the benchmark.

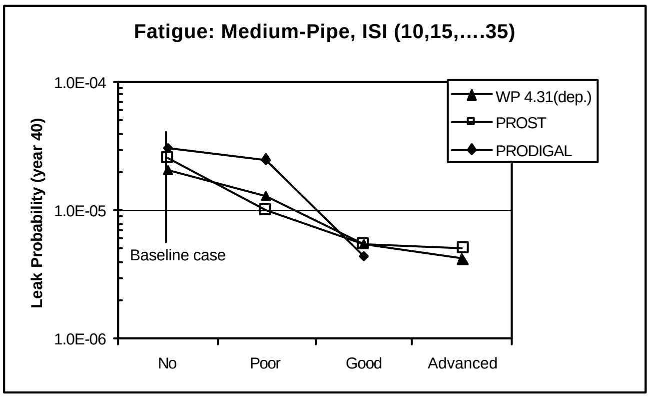

Fig. 11: Variation of inspection efficiency for fatigue.

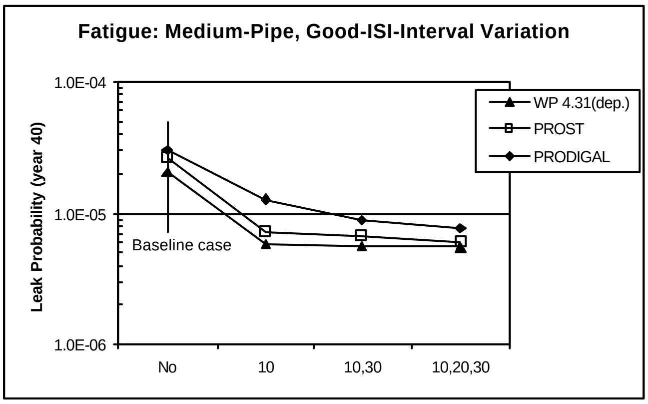

Fig. 12: Variation of inspection interval for fatigue.

2.5 Observations from the fatigue benchmark study

1. PRODIGAL, ProSACC, PROST and WinPRAISE reflect the expected trends by changing the investigated input parameters.
2. All investigated codes demonstrated to work in a wide range of leak probabilities by changing input data to extreme values. The range covers very small values from 1E-13 up to unity.
3. The resulting accumulated leak probabilities after 40 years show a good quantitative agreement between the different codes for the small and large pipe size and a very good agreement for the medium size pipe. From this behaviour one can conclude that the different failure criteria, stress intensity factor calculations and statistical methods of the codes have no strong effect on the resulting leak probability.
4. In some special cases a non expected trend or larger differences to the general results occur. They could be explained from the different basic assumptions and treatments in the codes. It is important that users of the codes are aware of these differences.
5. The accumulated leak probability after 40 years was mostly influenced by a variation of crack depth distribution, crack growth constant and maximum load.

2.6 Requirements for Structural Reliability Models used in a RI-ISI process

As an outcome from the benchmark study the following list of requirements are formulated that should be fulfilled by a suitable SRM and the associated software for application in RI-ISI studies.

1. The SRM theory and technical basis should be published and independently reviewed.

2. The SRM and the associated software should address the relevant damage mechanisms under consideration.

3. The SRM and the associated software should be able to evaluate failure probabilities both for leak events and ruptures.

4. A sensitivity study using the SRM and the associated software should be presented, addressing the relevant damage mechanism under consideration. In the sensitivity study failure probabilities, for events varying from small leaks to ruptures, should be evaluated for variations of input parameters and shown to be consistent with expectations and the given SRM theory assumptions.

5. Sample calculations of the SRM and the associated software should be presented where the assigned input parameters should be described and sources of the data assignments should be given. The probability distributions and internally assigned (hardwired) parameters (if any) in the SRM software should be documented and the reasons stated. Also the limitations of the SRM software should be clearly identified.

It is also strongly recommended that the SRM software should be benchmarked against at least one other publicly available SRM software for the relevant damage mechanism under consideration. The report of this benchmark study should be published and independently reviewed.

The SRM software should also be benchmarked against operating experience using actual plant failure frequencies. For damage mechanisms where no ruptures have occurred, leak frequencies may be used for this comparison.

3 CONCLUSIONS AND OUTLOOK

With the structural-reliability methodologies available today it is in principle possible to calculate quantitative leak and break probabilities for certain damage mechanisms. Trends can be quantitatively identified with regard to the change in influencing parameters. Limitations regarding the ability to use the codes within the framework of probabilistic safety analyses (PSA) are observed to exist in particular with respect to the validity of absolute leak and break probabilities. The results sometimes strongly depend on the uncertainties attached to relevant input parameters, such as crack geometry and expected loads, as well as certain parameters for the characterisation of the damage mechanisms. In general, structural reliability codes are valuable tools supplementing the methods applied so far within the framework of PSA for the estimation of risk of core damage or large early release originating from failure of passive components. In the presented study, only SCC and fatigue from pre-existing cracks have been benchmarked. Further developments of SRMs are needed to correctly assess the probabilistic aspects of initiating SCC and initiating fatigue cracks as well as erosion-corrosion and thermal stratification.

The nuclear regulatory bodies in Europe have formed a working group (Nuclear Regulatory Working Group NRWG, Task Force on RI-ISI). They have produced a report [12] where the common views about RI-ISI are presented. These are the following:

1. The introduction of RI-ISI must be in accordance with legal and regulatory framework of the European countries.
2. An ISI programme must be in place that is consistent with the defence-in-depth philosophy.
3. Risk-informed changes to ISI programmes must maintain safety margins against leakage and failure.
4. Risk should be reduced to a level derived from national legal requirements, regulations and regulatory guidance. When changing to a RI-ISI programme, risk reduction or risk neutrality should be achieved.
5. RI-ISI programmes should be monitored using performance measurement strategies.

Utility representatives have also expressed their views through the ENIQ Task Group on Risk. Their report [13] gives guidelines for using RI-ISI for ENIQ member countries. It is a comforting observation that both the ENIQ report [13] and the NRWG report [12] express views which to a large extent are in agreement.

The benchmark results within the NURBIM project should provide a valuable contribution within the objective to obtain a common view on applying RI-ISI procedures in Europe. Another step is to directly benchmark different RI-ISI procedures applied on a real Nuclear Power Plant. Such efforts are now planned within the so-called RISMET project [14].

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