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Comparative Study of Approaches to Estimate Pipe Break Frequencies

Kaisa Simola
Urho Pulkkinen
Heli Talja
Arja Saarenheimo
Päivi Karjalainen-Roikonen

VTT Industrial Systems, Finland

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Abstract

The report describes the comparative study of two approaches to estimate pipe leak and rupture frequencies for piping. One method is based on a probabilistic fracture mechanistic (PFM) model while the other one is based on statistical estimation of rupture frequencies from a large database. In order to be able to compare the approaches and their results, the rupture frequencies of some selected welds have been estimated using both of these methods. This paper highlights the differences both in methods, input data, need and use of plant specific information and need of expert judgement. The study focuses on one specific degradation mechanism, namely the intergranular stress corrosion cracking (IGSCC). This is the major degradation mechanism in old stainless steel piping in BWR environment, and its growth is influenced by material properties, stresses and water chemistry.

Key words

Probabilistic fracture mechanics, IGSCC, risk-informed in-service inspections, pipe break frequency

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NKS Secretariat
P.O. Box 30
DK – 4000 Roskilde, Denmark

Phone +45 4677 4045
Fax +45 4677 4046
www.nks.org
e-mail nks@catscience.dk

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Forewords

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1 Introduction

Risk-informed in-service inspection (RI-ISI) approaches aim at re-defining the inspection locations in an optimal way, leading to both increase in safety and decrease of inspection costs. The main inputs for the decision making are the estimates of consequences obtained from probabilistic safety assessments (PSA) and pipe rupture probabilities. In RI-ISI methodology, the piping systems are divided into segments, and for each segment the probability of degradation and consequence of a pipe failure is evaluated. The results of these evaluations are placed in a risk matrix or diagram. The basic idea is to reduce inspection activities in locations with low risks and find out the more risky locations where to concentrate inspection efforts.

The implementation of RI-ISI methodology calls for more accurate estimates of pipe rupture probabilities related to various degradation mechanisms, in order to enhance the bases for decision making. Further, there is lot of interest to update the pipe rupture frequencies used in PSAs, because they often originate from the reactor safety study WASH-1400 dating from nearly 30 years ago, and are criticised to be highly conservative.

Quite recently two approaches to estimate pipe leak and rupture frequencies for piping in Swedish BWRs have been introduced and applied. A pilot study to apply a piping failure database to estimate the leak and rupture frequency in reactor coolant pressure boundary (RCBP) piping was conducted in 1998. The LOCA frequencies of the Barsebäck 1 RCPB piping were estimated statistically on a basis of a large data base consisting of operating experience of set of nuclear power plant (BLAP-project, Lydell 1999). At the same time, a method based on a probabilistic fracture mechanistic (PFM) model was developed during the NKS/RAK-1 project (Andersson 1997), and the methodology has been applied to establish ISI-priorities for piping components at Oskarshamn 1 (Brickstad 1999).

There is interest to compare the results obtained with both of these methods. In NKS/SOS-2.1 project, the rupture frequencies of some selected welds from B1 were determined by using the same probabilistic fracture mechanistic codes (PIFRAP, PROPSE) as were applied in the Oskarshamn RI-ISI study, and the results were compared to the earlier obtained estimates from the BLAP-project.

This report describes the comparative study of the approaches, highlights the differences both in methods, input data, need and use of plant specific information and need of expert judgement. The assumptions and limitations of the models are summarised, and the differences in the quantitative results are discussed. Based on the results of this comparative study, recommendations for use of the above-described methods for estimation of LOCA frequencies and pipe degradation evaluation for RI-ISI application are given. The study focuses mainly on one specific degradation mechanism, namely the intergranular stress corrosion cracking (IGSCC), which is the major degradation mechanism in old stainless steel piping in BWR environment. However, as susceptibility for vibration fatigue has also been identified in some of the welds according to one of the studies, this issue will be shortly discussed.

In chapter 4, we present the comparison of results obtained by the two methods.

2 Description of the statistical approach used in BLAP project

The approach in BLAP-project was based on the use of a large database with world-wide information on NPP systems' pipe cracks and leaks, and the use of plant specific information. The generic data that was judged to be applicable to provide information on the crack and leak frequency of the system under consideration was selected from the database. This information was used to obtain system level rupture frequencies due to specific degradation mechanism, and this frequency was further divided among the piping components susceptible to that degradation. In the following, we first describe shortly the contents of the SKI-PIPE database at the time of the BLAP-project. After that we summarise the procedure that was used to estimate the weld-specific rupture frequencies due to IGSCC.

2.1 SKI-PIPE database

SKI-PIPE is a periodically updated database on piping failures in commercial nuclear power plants. At the time of BLAP-project the database covered the period 1970-1998 including more than 3000 events.

The database covers almost all, currently operating commercial BWR units except the Japanese plants. The database contained about 800 failure reports on weld failures due to IGSCC in BWRs.

The events are classified as either *crack*, *pinhole leak*, *leak* or *rupture*. The term rupture implies a sudden major failure having a significant effect on plant operation.

The database provides leak frequencies classified according to the expected degradation mechanism, pipe dimension, and system group. (E.g. "RCS, DN 250, IGSCC").
In this report we refer to the contents of the database

2.2 Estimation procedure for weld-specific rupture frequencies due to IGSCC

In the following, we describe the procedure to estimate the leak and rupture frequencies of a single weld or other piping component due to IGSCC. We also comment each step in the procedure.

Within this limited study, we are not evaluating the qualitative judgement done in the data pooling phase and in the selection of representative data from the database.

Selection of data from SLAP database and review of Barsebäck piping data

The data from the database is selected to correspond the expected degradation mechanism and system and pipe dimensions in question. The data accounted for in the BLAP study was the world-wide BWR data. At the time of the BLAP-project, the database included nearly 800 weld failures due to IGSCC. The data used for the estimation of rupture frequencies contained 654 weld failures. The RCPB (Reactor coolant pressure boundary) piping data is classified in the following two system groups:

- Reactor recirculation system (RCS) and
- Emergency core cooling, reactor water cleanup and residual heat removal systems (= SIR piping)

The database of BKAB, called PSA_VER2 includes information on weld locations, piping components (bends, elbows, pipes, tees), elevations, ISI histories, material data, results of the degradation and failure mechanism evaluations, and leak and rupture frequencies.

Estimation of baseline leak frequencies

The baseline leak frequencies for each system and pipe dimension group are estimated from the crack and leak data in the following way. The number of cracks and leaks from first 14 years of operation is used to form prior parameters for a gamma distribution. The prior distributions are selected so that the ratio of failures (k) and operating years (T) is reflected in the parameters α (shape) and β (scale): $\alpha/\beta \approx k/T$, and the variance is large.

The experience after the first 14 years of operation is used as evidence to update the prior distribution. In cases where there is no evidence from the whole observation period, the leak frequency is derived from a non-informative prior and applying the Jeffrey's rule. According to this rule, the prior parameters are α=0,5 and β=0 resulting in a posterior mean (0,5+k)/T.

This procedure is justified in the report by the fact that there is a very sharp decline in the number of IGSCC occurrences after roughly 13-15 years of commercial operation. This decline can be explained by the implementation of IGSCC mitigating measures, such as hydrogen water chemistry (HWC), weld overlay techniques and low carbon piping material. The procedure gives much more weight to the more recent data than to the experience from first 14 years of operation. In practice, the information from first 14 years of operation is neglected, since the selected prior parameters have very little effect on the posterior point estimates of crack and leak frequencies. As an example, we compare below the crack frequency obtained for RCS $100 \leq DN \leq 250$ piping calculated using this procedure and the alternative where all data is used to update a non-informative prior:

0-14 years: 112 cracks in 504 years
after 14 years: 8 cracks in 1078 years
total: 120 cracks in 1582 years

BLAP: prior parameters α=1, β=2, evidence only data from "after 14 years"
Crack frequency = (1+8)/(2+1078) = 8,33E-3 /reactor-year

All experience used as evidence to update a non-informative prior (α=0,5, β=0):
Crack frequency = (0,5+120)/1582 = 7,62E-2 /reactor-year

We can note that the difference between these results is roughly of an order of magnitude.

Estimation of conditional rupture frequencies for various pipe diameter classes

A conditional probability of rupture is determined separately for pipe diameter classes, but independent from system. It is assumed that the probability of rupture given cracks and leaks is binomially distributed. The numbers of cracks and leaks within the pipe diameter class are summed up, and represent the "number of demands". For medium and large diameter piping with no evidence from ruptures, Jeffrey's rule is applied to crack and leak data. The prior parameters of a non-informative beta-distribution are α=β=0,5. The posterior point estimate for the conditional rupture probability is obtained from $(\alpha+r)/(\alpha+\beta+n)$, where r is the number of ruptures (0) and n is the number of demands.

For the sake of comparison, the BLAP study included also the consideration of the 'Beliczey-Schulz' correlation to develop an anchored prior distribution. It is recognised by the author (Lydell 2001) of the BLAP study, that the development of an appropriate prior distribution remains somewhat controversial, and that it's probably an area where there is a technical reason for combining the statistical approach with PFM.

The conditional rupture probability for pipe dimension class $100 \leq DN \leq 250$ presented in the report did not correspond to the data on cracks and leaks, but according to Lydell (2001) this is a typing error and the probability should be 2,75E-3.

System and pipe dimension specific rupture frequencies

System and pipe dimension specific rupture frequency is obtained by multiplying the leak frequencies obtained in step 2 by the conditional rupture frequencies of the corresponding pipe dimension classes calculated in step 4.

It is not explained in the report why the crack data has not been used in this phase although they were used in determination of the conditional rupture frequencies. According to Lydell (2001) an approximation has been used here, but later a posterior conditional rupture probability based on an anchored beta based on Beliczey-Schulz has been constructed, which should be a more defensible approach.

Location specific rupture frequencies

In order to determine the component specific rupture frequencies from the rupture frequencies defined for system and pipe dimension groups, the baseline frequency is first divided among component locations.

The report provides location specific information of the IGSCC failure data. According to this statistics, e.g. more than 40 % of the failures (cracks and leaks) have occurred in bend-to-pipe welds.

The baseline frequency is partitioned in such a way that the corresponding percentage of the frequency is assigned to the weld population of that location.

It is not known whether the distribution of failures among locations reflects the variance in the IGSCC susceptibility of different locations or does the result reflect merely variation in the population of locations. According to Lydell (2001), more recent reviews of piping isometrics it seems that the distribution of failures *mainly* reflects the variation in the population.

The procedure used in the BLAP study assumes that the distribution of various weld locations in the application (B1) is comparable to the world-wide data. A problem with this approach is that if all possible locations are not present in the system where the baseline data is applied, the application of the method results in reduction of the rupture frequency. Some reduction – roughly 5% - seems to be inevitable since some data have not been classified in any of the locations (percentages do not sum up to 100%).

Component specific rupture frequencies

The component or weld specific rupture frequencies are obtained by dividing the location specific frequency by the number of components in similar locations. Further, the material properties are taken into account by dividing the weld specific rupture frequency by a factor 10 if the carbon content of the stainless steel is low. In case of a nuclear grade (NG) steel, this reduction factor is 20. These factors are judgmental, and based on quite old EPRI data.

It seems appropriate to have a difference of this order of magnitude in the rupture frequencies of piping of different materials. However, it can be questioned whether it should be done solely by crediting the better material or should the rupture frequencies be increased for piping with higher carbon content.

Table 1 summarises the above-described steps and our major comments.

Table 1. Steps of the BLAP procedure.

Input data	Model	Output	Comments
Crack and leak data from the database classified by system and pipe dimensions, first 14 years separated from more recent data	Prior parameters of gamma distribution reflect roughly the old data. Non-informative prior according to Jeffrey's rule applied if no data exists. Gamma prior updated with more recent data.	Estimates for crack frequency and leak frequency	The resulting estimates should be applied only to plant where IGSCC mitigation has been implemented.
Crack and leak data from the database classified by system and pipe dimensions	Jeffrey's rule applied to estimate conditional rupture frequency (conditioned on cracks and leaks)	Conditional rupture frequency for various pipe dimension groups	There is a typing error in number of events for 100<DN<250. It should be 181 (137 + 44) resulting to the conditional rupture probability 2,75E-03.
Previously calculated leak frequency and conditional rupture frequency estimates	Multiplication of the conditional rupture frequency by the leak frequency.	Rupture frequency (1/reactor-year) classified by system and pipe dimensions	The cracks are not included in this phase although they were included in the calculation of conditional rupture frequency.
Rupture frequencies, plant specific information on existing locations	The rupture frequency is partitioned for various locations according to the distribution in the database.	Location dependent rupture frequencies	If all possible locations are not present in the system, the total rupture frequency will decrease from its original value.
Location dependent rupture frequencies, number of welds and material properties	The rupture frequency is divided equally for all the welds in the "location group". If material is low carbon, the frequency is divided by 10, and in case of "nuclear grade" by 20.	Component specific rupture frequencies	The crediting for better material reduces further the original total rupture frequency. It might be more proper to account for the material also by increasing the rupture frequency of worse welds.

3 Probabilistic fracture mechanics approach

3.1 Description of the PIFRAP procedure

The probabilistic computer code PIFRAP (Bergman 1997) is meant for evaluation of the leak and rupture probabilities of a specific cross section with a certain stress state and possibly containing a circumferential growing crack due to stress corrosion cracking (IGSCC). Crack growth due to high cycle vibration is treated in a simplified way. The steps for the evaluation in pipes are described in the following. For more details on the approach, please see the references (Bergman 1997) and (Brickstad 1999).

Following assumptions are made for the probabilistic analysis (Bergman et. al. 1997):

1. The loading is deterministic.
2. The crack growth law and its parameters are deterministic.
3. The initial crack depth is fixed (1 mm).
4. The crack initiation probability during time interval (t_i, t_i+dt) is given by $f_i(t_i)dt$.
5. The initial crack length is random with the probability density function $f_{al}(l_0)$.
6. The probability of not detecting a crack at an in-service inspection is p_{nd}(a) i.e. it depends on crack depth only.
7. The probability of not detecting a leak rate of a size corresponding to the detection limit *d* is p_{ld}.

The crack initiation time is modelled with a uniform distribution, which is based on observed stress corrosion cracks in Swedish BWRs. It is assumed that the depth of an initiated crack is 1 mm, and the length is modelled with a truncated exponential distribution. The parameters of the distribution have also been estimated from observed Swedish IGSCC cases. The Swedish experience consists presently of 98 IGSCC cases.

An initiated crack is assumed to grow by IGSCC both in depth and length direction with a deterministic rate. Operating stresses and weld residual stresses are used to determine the stress intensity factor along the crack front, which is assumed to determine the growth rate. The crack growth is evaluated in PIFRAP with a separate code, LBBPIPE. LBBPIPE predicts the growth of an initial circumferential surface crack in a pipe both for the part-through crack up to wall penetration and for the leaking crack until failure. When the crack has become a through-wall crack, consideration is given to complex crack shapes. This is due to the observation that the length of a through-wall crack is usually much smaller at the outer surface than at the inner surface.

The IGSCC crack growth is assumed to follow equation (1).

$$\frac{da}{dt} = C_0(K_I - C_I)^n \qquad (1)$$

where K_I is the stress intensity factor and the parameter C_I is a threshold value for IGSCC.

Figure 1 shows the possible events for a growing crack.

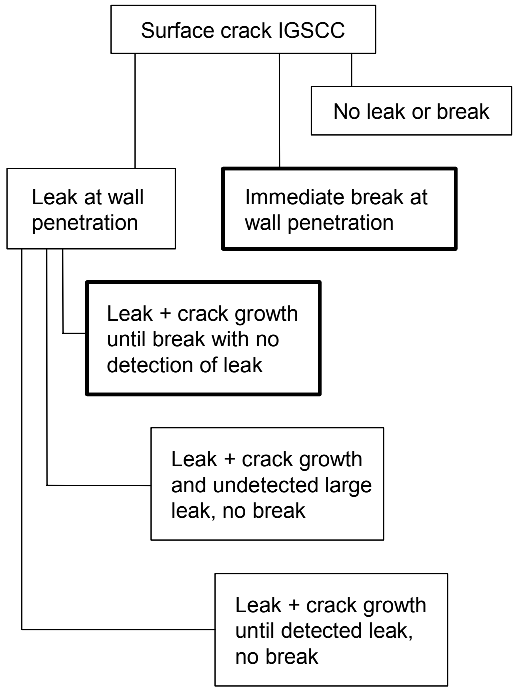

Figure 1. Flow chart of different events for a stress corrosion crack in a pipe (Brickstad 2000). Events leading to pipe rupture are marked with thick borders.

For a through-wall crack, the vibration fatigue in combination with IGSCC is taken into account in a simplistic way. If the stress intensity factor exceeds a threshold value K_{th}, which is assumed to be 4 MPa√m (Brickstad 2001), fracture is assumed to occur instantly although the crack growth until fracture would typically need a few hours or some days.

The crack can grow through the wall and cause a leak only if the time needed to have a through wall crack is less than the remaining lifetime of the plant and the crack is not detected in inspection. The probability of crack detection in inspection is assumed to depend on the relative depth of the crack and the quality of the inspection. If a crack is detected, it is assumed that a break is excluded either be reparation or sufficient future monitoring.

A rupture of a pipe can occur either if there is a non-Leak-Before-Break situation or if the leakage has not been detected in inspections or by leak detection. The probability of leak detection is handled through assuming a random behaviour of the leak rate, which is compared to the detection limit d. This gives the on-detection probability of the leak, p_{ld} The leak rate is calculated in LBBPIPE with a separate code, SQUIRT. The calculated leak rate is assumed to be normally distributed for varying crack morphology parameters. The deterministic value calculated by SQUIRT is assumed to be the mean value (Bergman et. al. 1997).

For a crack with a length of l_0, the conditional probability of rupture during the remaining life after the time *t* is calculated analytically from the equation:

$$p_{f0}(t,T,l_0) = p_{ld}(l_0) \int_{t_i=\max(0,t-t_f)}^{T-t_f} f_i(t_i) \prod_{j=j_1}^{j_2} p_{nd}[a(t_j - t_i)]dt_i \qquad (2)$$

where

$p_{ld}(l_0)$ = probability of not detecting a leak (detection limit is *d*)

$f_i(t_i)$ = probability density function for initiation time t_i

$p_{nd}(a)$ = non-detection probability of a crack with depth *a*

T = service time of the component

t_F = time of fracture

t_j = inspection times.

The time window used in time integration ensures that only inspections after initiation and before rupture are considered. Further explanations of the equation (2) can be found e.g. in the reference (Brickstad 1999).

The rupture probability for a pipe section is obtained by integrating Equation 2 as follows:

$$p_f(t,T) = \int_{l_c}^{2\pi R_i} p_{f0}(t,T,l_0) f_{al}(l_0) dl_0 \quad . \qquad (3)$$

To obtain a leak, it is required that the crack has initiated, grown through the wall and has not been detected in inspections. For a rupture, it is additionally required that the leak has not been detected.

The steps of the PIFRAP model are summarised in Tables 2 and 3. The input data for the PIFRAP procedure is described in Appendix 1.

The rupture probabilities of piping where there is no susceptible degradation mechanism present, is estimated using the computer code PROPSE. For these piping, the PIFRAP would give a zero leak and rupture probability. PROPSE is a code developed for evaluating the failure probability of non-growing manufacturing defects from the welding process. These defects have a non-zero, but very small failure probability. The calculation is based on a FORM (First Order Reliability Method) technique to handle the probability data.

Table 2. Steps of the PIFRAP model: fracture mechanical calculation and treatment of in-service inspection.

Input data	Model	Output	Comments
Swedish data on IGSCC cracking (98 cases): cumulative number of IGSCC-cases, length distribution of observed cracks	Crack initiation with constant rate; fixed initial crack depth and truncated exponential distribution for initial crack length	Estimate for crack initiation time, initial crack length l_0	
Geometry, initial crack size, crack initiation time, service stresses, welding residual stresses, crack growth law parameters	Deterministic crack growth by IGSCC (LBBPIPE program). After growing to a through-wall crack, a complex crack shape is assumed.	Crack growth a(t), l(t), t_L (leak), t_F (rupture)	
Geometry, instantaneous crack size, complementary failure load data, welding residual stresses, material parameters	Comparison of loading to plastic limit load and load induced J-integral against critical value	Information on endurance/ break	Due to the low occurrence frequency, no crack growth due to the complementary failure load is considered
Geometry, instantaneous crack size, high frequency vibration stress amplitude, threshold value ΔK_{Ith}	For a through-wall crack: comparison of stress intensity factor range to the threshold value	Crack growth a(t), l(t), t_L (leak), t_F (rupture)	Instantaneous break is assumed when the high frequency vibration stress causes $\Delta K_I > \Delta K_{Ith}$
Crack depth, wall thickness, coefficients C_1 and C_2 depending on type of inspection team.	Non-detection probability is $p_{nd} = 1 - \Phi\left[C_1 + C_2 \ln(a/t)\right]$ where ϕ is normalised Gaussian distribution.	Non-detection probability of the crack $p_{nd}(a)$	The detection probability is assumed not to depend on the crack length. If a crack is detected, break is excluded either be reparation or sufficient future monitoring.

Table 3. Steps of the PIFRAP model: leak and rupture estimation.

Input data	Model	Output	Comments
calculated fracture mechanical parameters, morphology parameters, external pressure	SQUIRT code	leak rate $m(t_F)$	Elastic COD and COA-values plasticity corrected
Leak rate calculated by SQUIRT and leak rate detection limit d	Random properties of leak rate accounted using normal distribution..	Leak detection probability	
Initial crack length l_0, Probability density function $f_{al}(l_0)$ and $f_i(t_i)$ are based on 98 IGSCC-cases in Swedish SS grid welds	Fracture probability, random properties of the initial crack length $t_F(l_c)=T => l_c$ Fracture probability, random properties of the initial crack length $(t_L(l_c)=T => l_c$?)	Conditional probability of rupture p_f Conditional probability of a leak p_L at a certain leak rate level $m(t_L)$. If $m(t_F)< m(t_L)$; $t_L=t_F$	
p_f	divided by (T-t)	Probability of rupture as a mean value per reactor years for the remaining operating life time	
p_L	divided by (T-t)	Probability of a certain leak rate as a mean value per reactor years for the remaining operating life time	

3.2 Some comments on the PIFRAP procedure

Fixed crack growth law parameters are applied during the whole time interval corresponding to the total service life of the plant. However, a change from normal water chemistry (NWC) to a hydrogen water chemistry (HWC) has resulted in significant reduction in the crack growth rate. This has been treated by using some averaged crack growth law parameters. The way in which this averaging is performed may affect significantly the results. Thus a sensitivity analysis would be very strongly recommended. In the new NURBIT program (Brickstad & Zang 2001), the possibility to change crack growth law parameters according to the water chemistry modification has been realised.

The assumption of a constant initiation rate for all parts of piping system may be too simplified and yield in some cases to very conservative and in some cases even to non-conservative predictions. Correspondingly, the assumption of a constant initiation rate in time does not consider the ageing effects. The choice of a constant initiation depth may seem somewhat arbitrary. At least it would be interesting to compare the value to the Swedish database, which has been used to define the crack initiation length. The choice of the initiation depth value of 1 mm has been rationalised by the validity limits of classical fracture mechanics (Brickstad 2002).

Generally, the consideration is limited to the case that only one crack can initiate in a weld, which may be a somewhat non-conservative assumption. If a crack is detected, it is assumed in PIFRAP, that the crack is immediately repaired. If the repair weld is also susceptible to IGSCC, it is possible that a new crack may be initiated. In NURBIT (Brickstad & Zang 2001) it is possible to reset the starting time of the weld to the year of the repair, if it is known that a repair has taken place.

In NURBIT (Brickstad & Zang 2001) it is also possible to treat the effect of changes in the piping. E.g., if a part of a piping system is replaced at a certain time, the counting can correspondingly be restarted. In NURBIT it is also possible to do a distinction in the consideration for the A- and B-sides of the weld (Brickstad & Zang 2001). This can be necessary due to different material behaviour and/or due to that different inspection methods or intervals have been used on the different sides of the weld.

Generally we find that the choice between deterministic and random variables would need some more thorough justification.

In summary, most of the development needs we found in the PIFRAP method have actually already been realised in the new NURBIT code.

4 Conclusions from the approaches

4.1 Purpose of the approaches

We limit here our conclusions mainly to the PIFRAP model and to the estimation of IGSCC failures in BLAP. Other phenomena than IGSCC are left for only minor attention.

The approaches described above have different purposes, which affect the comparison. Since the approaches aim at different things, the models and methods are selected in different way. The methods emphasise different aspect of the phenomena under analysis, which leads to differences in results. The comparison of approaches with different purposes is not a straightforward task, and in some cases it may be even impossible.

Table 4 summarises the different objectives of the approaches. One could say that BLAP is more PSA oriented, and PIFRAP RIISI-oriented. The principal aim of the BLAP approach has been to obtain better LOCA-frequency estimates, based on extensive use of operating experience of nuclear power plants. To reach this objective, the statistical analysis is a natural approach. PIFRAP directs towards explicit modelling of crack growth, failure mechanism and in-service inspections.

Common to both approaches is that they give estimates for location or weld specific pipe rupture probabilities. Thus, both approaches should support the applications of risk-informed in service inspection.

Table 4. Purposes of the approaches.

BLAB	**PIFRAP**
• Estimation of location specific LOCA-frequencies for PSA • Support for risk-informed in-service inspection evaluation • Extensive utilisation of generic nuclear power operating experience • Combination of plant-specific and generic pipe failure data • Direct application of statistical methods and analyses	• application probabilistic fracture mechanics to estimate mechanism-specific pipe rupture probabilities for individual welds • explicit modelling of the effect of inspection and failure detection on pipe rupture probability • evaluation of inspection policies or risk-informed in service inspection policies

4.2 Use and interpretation of data

For the application of both approaches, some component specific information from the plant is required. In the statistical approach, it is clear that the information requirements for characterising the individual welds cannot be too detailed. The requirements reflect the degree of details of the information available in the large database. In the case of PFM approach very detailed information is needed as input for the code because the models are based on the physical or empirical dependencies between e.g. environmental and material properties, and the degradation process. The realistic operating conditions and inspection programme can be taken into account in the modelling.

The plant specific information used in the two approaches is summarised in Table 5.

Table 5. Plant specific information used in the models.

BLAP	**PIFRAP**
• Component dimensions • Material properties (mainly carbon content) • Component location and population	• Component dimensions • Weld residual stresses • Material properties • Loads and stresses • Water chemistry (HWC) • Inspection frequency

The main purpose of the statistical approach is to use to as large extent as possible the operating experience from all relevant nuclear power plants. The relevant information from the database is selected on the basis of plant and system type, pipe dimensions and expected degradation mechanisms. The events in the database are classified as cracks, leaks and ruptures.

In the PFM model, the Swedish experience on IGSCC has been considered in two cases. The crack aspect ratio distribution has been estimated from a data that includes the geometry of analysed IGSCC cracks in Swedish BWRs. The number of observed cracks has been used to estimate parameter for the initiation frequency.

It is worth noticing that the data on IGSCC events in Swedish BWRs is common for both applications.

The use of operating experience from other nuclear power plants in the two approaches is summarised in Table 6.

Table 6. Operating experience from other plants used in the models.

BLAP	**PIFRAP**
World wide IGSCC data: • Number of cracks • Number of leakages • Number of ruptures (=0)	Swedish IGSCC crack data: • Depth and length of cracks • Total number of cracks

In the statistical approach where failure frequencies are estimated directly from the operating experience, no other data sources than the above described plant specific information and world-wide crack, leak and failure data has been considered.

Some parameter values in the PFM model are taken from literature. Such parameters are e.g. the crack growth rate and the non-detection probability in the inspection model. The values of the parameters have been estimated from large data, the relevance and applicability of which cannot be judged within this study. For more details on the origin of model parameters, see the references e.g. in (Brickstad 1999).

4.3 Models and results

Due to conceptual difference between the approaches, the comparison of the models and results is not quite simple. The statistical model works more or less like a "black box" model where many of the actual phenomena are not taken into account. On the other hand the PFM model includes explicit modelling of crack initiation and growth, inspections and other phenomena. The results obtained by the both approaches do not have exactly the same meaning.

The definition of pipe failures is an important part of the models discussed here. BLAP utilises the SKI-PIPE database, where failures are classified as *crack*, *pinhole leak*, *leak* or *rupture*. An event classified as *crack* implies that the crack tip did not penetrate the pipe wall. *Pinhole leaks* are defined as cracks of limited width and length penetrating the pipe wall leading to visible water seepage or drop leakage. Event involving at-power leaks discovered trough normal global or visual leak detection systems are classified as *leaks*. The term *rupture* refers to a sudden, major piping failure having significant effect on plant operations. The above definitions determine the quantitative results in two ways. First, they are used in the interpretation of data. Secondly, they form the basis to the BLAP-rupture frequency models. For the case, in which there is an active failure mechanism (e.g. IGSCC, TGSCC) the model is

$$f_R = f_L \times P(R \mid L) \tag{4}$$

in which f_R is the rupture frequency, f_L is the leakage frequency, and $P(R|L)$ is the conditional probability of rupture given that a leakage has occurred. In the model for piping susceptible to water hammer, the structure is similar. When there is no active degradation mechanism, the rupture frequency is developed directly from rupture data.

PFM method defines the failure concepts in the following way. It makes difference between *small leak* and *rupture*. *Small leak* is defined as a leak, that is well below the limit at which the loss of coolant can not be compensated by the normal feed-water systems. The small leak probability represents the probability that the crack penetrates the pipe wall, and that the leak rate is very small and often too small to be detected. This could be interpreted as the counterpart of leakage frequency in the BLAP-approach. *Rupture* is defined as an event, in which the pipe section breaks into two pieces, or at least creates a large bending angle with only a limited ligament to hold the pipe ends together. This corresponds to the rupture frequency in the BLAP-approach.

The BLAP-approach yields a time independent location specific pipe rupture frequency. The model is that the pipe ruptures occur according to a Poisson process with constant intensity. The intensity depends on factors discussed above. The probabilistic fracture mechanics model gives a time dependent probability of pipe rupture, i.e. the probability that a rupture occurs before certain time point, given the inspection policy. In this report the probability is converted to a frequency by determining the average probability of rupture during the considered time interval, and dividing it by the length of the interval.

In the PFM model, the stochastic dynamics of the crack growth and detection are described by assuming that the time to crack initiation is a random variable, and by taking into account the reliability of the inspection method and leak detection. As opposite to this, the applied BLAP model is static and it doesn't explicitly take into account the impact of inspections. Lydell (1999) discusses the possibility to apply time dependent leak/rupture frequency, but the model has not been applied in the BLAP study.

In the case study, the pipe rupture frequencies were determined for selected welds at Barsebäck 1 nuclear power plant by using the above mentioned two methods. Sensitivity and uncertainty analyses were not required. In practice, it is important to see how sensitive the results are to modelling assumptions and input parameters.

The PFM approach is a parametric model, and sensitivity analyses can be made with respect to changes in input parameter values. It is possible to identify the impact of assumptions, input data and "sub-phenomena" on the results. Further, it is rather easy to change the structure of the model and some basic assumptions. This kind of sensitivity analyses have been made in other connections, see e.g. (Brickstad 1999). One can state that the parametric PFM model supports well sensitivity analyses. However, there is no written guidance for sensitivity analyses. The uncertainty of parameters is not taken into account in the model in the form of probability distributions. This would probably require a Monte-Carlo simulation model.

In the case of BLAP-approach, the results are sensitive e.g. to the principles used in pooling of the data. In principle, it is possible to analyse how sensitive the results are to the assumption behind data pooling, but it may be rather difficult to make it systematically. Thus, the nature of the approach doesn't support sensitivity analyses, and there is no written guidance on how to make these analyses. However, it must be recognised that BLAP study was intended as demonstration of a principle, and the approach has subsequently been formalised into a step-by-step analysis procedure, supporting better sensitivity analyses.

The possibility to analyse statistical uncertainty due to limited amount of data is in principle an inherent property of Bayesian methods applied in the BLAP-approach. However, the expert judgements used in interpretation and pooling of data have probably greater impact on the overall uncertainty of the results. It would be possible to take the expert judgements into account by applying Bayesian models, but the use and interpretation of such a model is difficult.

The PIFRAP method has been validated informally by comparing the leak rates with observed leak frequencies, and comparing the simulation results with those of the

WinPRAISE-code (Harris & Dedhia 1998). In addition to this, a lot of sensitivity analyses have been made (Brickstad 1999). In principle, the validation of the model can be done piece-wise by reviewing separately the sub-models.

The validation of BLAP approach is more problematic. The model leans largely on selection of data from a database, interpretation and pooling of the data. The dependence on the subjective judgements of the analyst is not easily traceable. In order to be validated, the procedures of BLAP-approach should be documented in a more detailed way. A detailed uncertainty analysis is important and it is recommended to have it as an integrated part of future applications

The traceability of results is related to the validity of the method. It is not easy to trace the calculations of the BLAP-approach, but this is partly due to the fact that all documentation is not included in the available material. More generally it can be said that traceability may often be problematic case with statistical methods based on large amount of data. In the case of PIFRAP, it is easier to trace or understand the results.

In a recent paper, Wilkowski et al. (2002) conclude that as both statistical (BLAP type) and PFM type approaches have different strengths and weaknesses, they should be considered as complementary and so it would be very advisable to use them together in combined analyses. They consider three different failure databases. Wash 1400, NUREG/CR-5750, Appendix J (published 1999) and the SKI databases. According to their point of view, the main concern in this approach is the (deficient) service history coverage for estimation of rare events like LOCAs. As regards to the PFM methods, Wilkowski et al. comment on the highly variable estimates and recommend strongly their benchmarking against actual service experience.

5 Comparison of the calculated pipe break frequencies

5.1 Welds selected for the comparative study

Altogether 28 welds were selected by BKAB for the comparison. 19 of them are located in the recirculation piping system (313) and 9 in residual heat removal system (321). These welds were selected so that there was significant variation in the loads and material properties. The dimensions of the piping vary between DN 100 and DN 600. Some information on these piping is given in Tables 7-10.

Table 7. Information related to the analysed DN 100 piping welds in system 313.

Weld Location	Component	Op Temp	Material A-side	Material B-side	Carbon content (side)
Pipe-to-Tee	B1	>150	19Mn6	X5CrNi18.9	>0,04 (A)
Bend-to-Pipe	B2	>150	X5CrNi18.9	X5CrNi18.9	>0,04 (A)
Pipe-to-Valve	B3	>150	X5CrNi18.9	-	>0,04 (A)
Pipe-to-Valve	B4	>150	X5CrNi18.9	X5CrNi18.9	>0,04 (A)
Bend-to-Pipe	B5	>150	X5CrNi18.9	X5CrNi18.9	>0,04 (A)
Pipe-to-Tee	B6		X5CrNi18.9	19Mn6	>0,04 (A)
Pipe-to-Pipe	B13	>150	X5CrNi18.9	A312TP316L	>0,04 (A)
Bend-to-Pipe	B14	>150	316L-NG	316L	<0,03 (A)
Bend-to-Pipe	B15	>150	316L-NG	A312TP316L	<0,03 (A)
Pipe-to-Pipe	B16	>150	316L-NG	X5CrNi18.9	<0,03 (A)
Bend-to-Pipe	W1	>150	X5CrNi18.9	X5CrNi18.9	>0,04 (A)
Bend-to-Pipe	W5	>150	X5CrNi18.9	X5CrNi18.9	>0,04 (A)
Bend-to-Pipe	W6	>150	X5CrNi18.9	X5CrNi18.9	>0,04 (A)
Bend-to-Pipe	W7	>150	X5CrNi18.9	X5CrNi18.9	>0,04 (A)

Table 8. Information related to the analysed DN 600 piping welds in system 313.

Weld Location	Component	Op Temp	Material A-side	Material B-side	Carbon content (side)
Safe-end-to-Pipe	B1	>150	A508	19Mn6	>0,04 (A)
Pipe-to-Venturi	B2	>150	19Mn6	Inconel weld	0,03-0,04 (B)
Pipe-to-Pump	B4	>150	19Mn6	19Mn6	CS/SS-clad (A)
Bend-to-Pipe	W3	>150	19Mn6	19Mn6	CS/SS-clad (A)
Venturi-to-Valve	W5	>150	1.4301	GX6CrNiMo19,10	0,03-0,04 (A) <0,03 (B)

Table 9. Information related to the analysed DN 150 piping welds in system 321.

Weld Location	Component	Op Temp	Material A-side	Material B-side	Carbon content (side)
Pipe-to-Valve	B2	>150	1.4301	1.4550	>0,04 (A&B)
Pipe-to-Valve	B3	>150	1.4550	1.4301	>0,04 (A&B)
Bend-to-Pipe	B5	>150	1.4301	1.4301	0,03-0,04 (A) >0,04 (B)
Bend-to-Pipe	W1	>150	1.4301	1.4301	0,03-0,04 (A) >0,04 (B)
Bend-to-Pipe	W2	>150	1.4301	1.4301	>0,04 (A) 0,03-0,04 (B)
Bend-to-Pipe	W6	>150	1.4301	1.4301	>0,04 (A) 0,03-0,04 (B)

Table 10. Information related to the analysed DN 250 piping welds in system 321.

Weld Location	Component	Op Temp	Material A-side	Material B-side	Carbon content (side)
Bend-to-Pipe	W9	>150	1.4301	1.4301	0,03-0,04 (A) >0,04 (B)
Bend-to-Pipe	B7	>150	1.4301	1.4301	>0,04 (A) 0,03-0,04 (B)
Tee-to-Pipe	B8	>150	1.4301	19Mn6	>0,04 (A)

5.2 Results of the analyses

In this section we compare the numerical results obtained with the two approaches. In the application of the PFM models, three different cases were analysed:

- In-service inspection (ISI) are not taken into account at all
- Only ISI history is considered but not future inspections
- Both earlier and future inspections are accounted for.

In the following comparison, we consider only the third case, which is the most realistic one and would best correspond to the BLAP estimation. In the cases where no degradation mechanism was identified, the rupture frequency was evaluated with PROPSE. If these analyses result in frequencies below 10^{-11}/year, a cut-off value 10^{-11}/year was used as the estimate.

Figure 2 shows the rupture frequencies for the selected DN 100 piping in system 313. It can be noted that the PIFRAP results have more variation. This is obvious, because the model uses more weld specific data (stresses). Both approaches give lowest rupture frequencies for welds B14 and B15. This is due to the material properties (316L-NG) that are accounted for in both approaches. In PFM analyses it is judged that no SCC can occur, and PROPSE gives the cut-off value 10^{-11} as result. In BLAP, the “nuclear grade” material is accounted by a factor 20 for welds B14, B15 and B16. The highest rupture frequencies calculated by PIFRAP, (welds B1, B2, B5, B6, W1 and W7) are explained by the presence of vibrations. The vibrations are not accounted for in the BLAP results. In the cases where SCC is the only degradation mechanism, the BLAP results are higher than those calculated by PIFRAP.

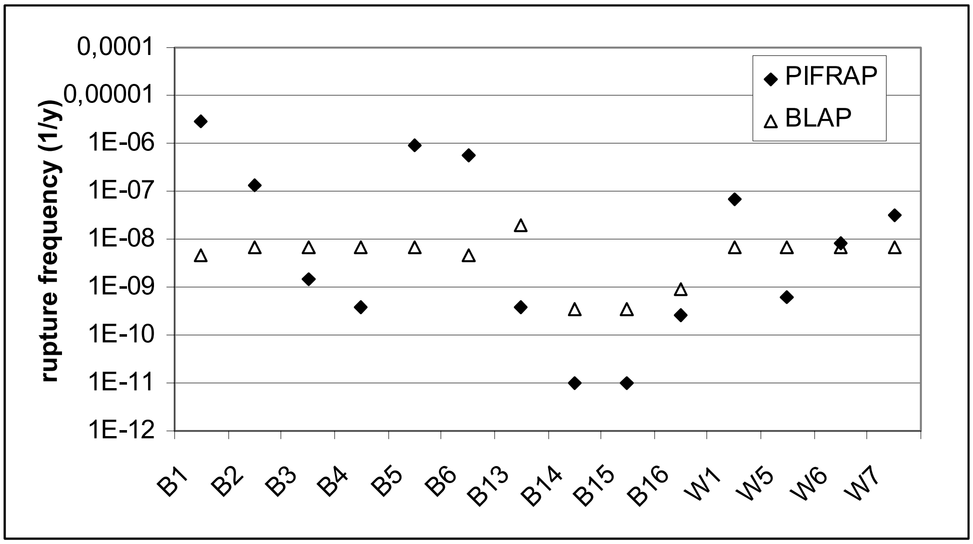

Figure 2. Calculated rupture frequencies for analysed DN 100 piping in system 313.

Results for the selected DN 600 piping in system 313 are presented in Figure 3. In the PIFRAP analysis, the low failure probabilities are explained in three cases by no known damage mechanism. In two welds, IGSCC is considered as a possible degradation mechanism, but the analysis results in negligible rupture frequency due to the low pipe system stresses and favourable residual stresses, which are typical for thick-walled pipes. In BLAP analyses, W5 is determined as a location with low carbon content, which reduces the rupture frequency. The accounting for location dependency causes the variation in the results. Bend-to-pipe welds (W3) are assumed to be the most prone locations for degradation.

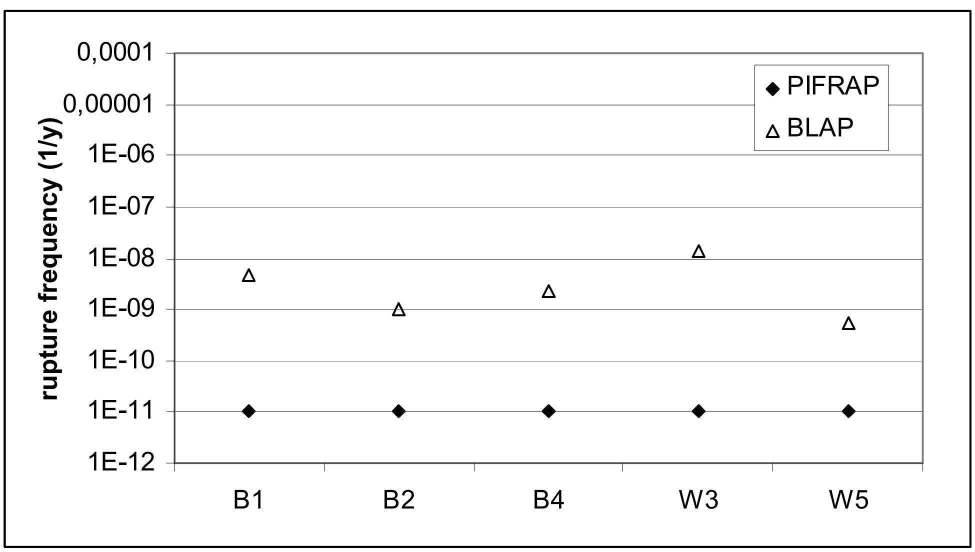

Figure 3. Calculated rupture frequencies for analysed DN 600 piping in system 313.

Figure 4 shows the results for system 321, DN 150 piping welds. In PIFRAP results, the highest values (B3, W1, W2 and W6) are due to large thermal expansion stresses or large

SRV bending stresses. In the results of BLAP, the lower rupture frequency estimates of welds B5 and W1 are due to the material properties. It seems that the material influence is determined from the carbon content of the A-side of the weld.

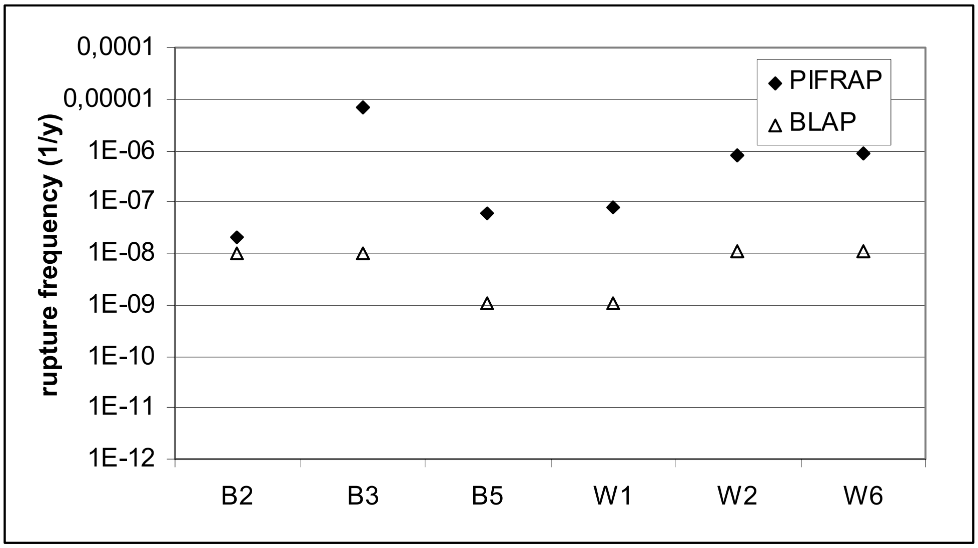

Figure 4. Calculated rupture frequencies for analysed DN 150 piping in system 321.

The results for the three welds in DN 250 piping in system 321 are presented in figure 5. In PIFRAP results, the high rupture frequency estimate of B8 is due to large thermal expansion stresses and the rather large vibration bending stress amplitude. In BLAP results, the difference of one order of magnitude between the results of B7 and W9 originates from the accounting for the material carbon content of the A-side: W9 is classified in the analysis as "low carbon" material. Compared to B7, B8 has a lower rupture frequency estimate due to its location. In the PIFRAP analysis, it is noted that vibrations are present in all three locations. BLAP analysis does not take the vibrations into account.

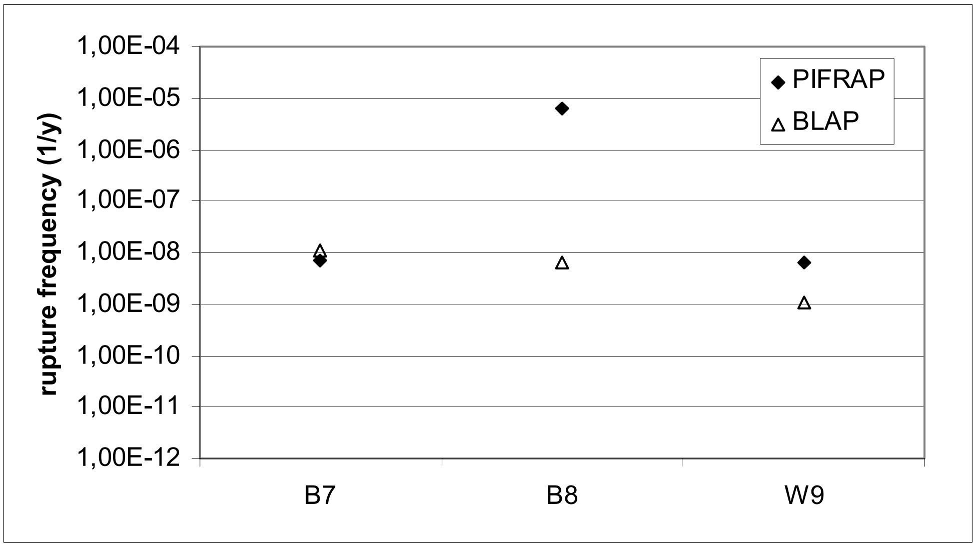

Figure 5. Calculated rupture frequencies for analysed DN 250 piping in system 321.

5.3 Concluding remarks from the comparison of estimated rupture frequencies

The comparison of the numerical results highlights the importance of the weld specific information and expert judgement. In some cases the material properties have been interpreted differently, which explains some large differences.

In several cases, the vibrations have been identified as a potential degradation mechanism together with IGSCC in the fracture mechanics analyses, but not in the BLAP analysis. According to the PIFRAP analyses, the high cycle vibration amplitude is sufficiently small that the stress intensity factor does not exceed the vibration threshold in the case of a surface crack. But relatively soon after the crack has penetrated the wall, the vibration threshold will be exceeded and a conservative assumption of an immediate rupture is made in the fracture mechanistic model.

The identification and evaluation of degradation mechanisms present in the piping segments have been documented in the BLAP background material available for this comparison. The considered mechanisms were vibration fatigue, thermal fatigue, water hammer and stress corrosion cracking. According to this documentation, the vibration fatigue is not applicable in 321 welds of diameter 100-250 mm. In the case of DN 100 piping welds of the system 313, vibration fatigue is considered as “feasible degradation mechanism given some specific coincidental factor(s)”. Although the database distinguishes between apparent cause and underlying cause, the analyses did not go beyond the apparent cause to try to differentiate between contributing factors. As the BLAP project covered all the relevant systems form the PSA point of view, the analysis could not be as detailed as in the case of the PIFRAP calculations, where only the selected 28 welds were considered.

The BLAP approach tries to account for such influencing factors as the weld location and piping material. These are the main means to obtain variation in component failure frequencies within piping of same dimension group in a system. It is understandable that the obtained rupture frequencies show less variation than those estimated using the PFM model with weld-specific information on loadings: the higher local stresses at geometrical discontinuities like bends and Tees lead to higher crack growth rate and higher failure probability. The manufacturing history may also have an effect on the local stresses e.g. depending on whether a stress relief procedure has been applied after welding or not.

If we sum up the results of all the analysed welds, the PFM results are two orders of magnitude higher than the BLAP results. This is due to the relatively high rupture frequencies of some welds calculated with the PIFRAP code. One reason for this may be the conservatism in rupture frequency calculation for welds susceptible for both IGSCC and high cycle vibrations. E.g. importance of vibrations in DN250 piping is not supported by the service data.

6 Conclusions

The results of the rupture frequencies obtained by the two alternate approaches are quite different, but one approach does not give systematically higher values than the other one. The rupture frequencies calculated by the PFM codes have larger variation, which is understandable since the models use weld specific information on stresses that may vary quite significantly.

Some of the differences may be explained by different expert judgements made while applying the models. As an example, both approaches take into consideration the material properties of the weld, but may have different interpretation depending on whether this information is from the A- or B-side of the welds.

Some differences are related to the different possibilities to account e.g. for weld-specific information. In some cases, the results are not directly comparable, because the considered degradation mechanisms are not the same. For instance the effect of vibrations is accounted for in the PFM modelling while the statistical approach considered only the IGSCC.

It is worth noticing that there are some common features in the two approaches, such as the use operating experience, i.e. information on observed cracks and leaks. While the PFM model uses Swedish data for estimating crack initiation and aspect ratio, statistical approach uses a larger database for estimating leak and rupture frequencies.

Compared to the pipe failure estimates in WASH-1400, both methods generally give significantly lower frequencies with the exception of some welds with high local stresses, where the PIFRAP code gives very high failure frequencies. The information based on statistical evidence should be taken into consideration, e.g. in updating of LOCA frequencies. For this purpose, the principles of the statistical approach might be sufficiently accurate, especially if it is completed with structured expert judgement. Although we have considered here only one degradation mechanism, corresponding database are being developed for other mechanisms too.

The probabilistic fracture mechanistic approach requires a lot of weld specific information from the stresses, and it may be argued that the approach may be too laborious for some applications. However, in RI-ISI applications where the procedure requires quite detailed analysis of the piping system, the quantification of leak and break probabilities may provide additional support for decision making with relatively small additional efforts.

Despite of large uncertainties related to the quantification of these probabilities, a probabilistic fracture mechanistic approach can be considered as an appropriate decision support in the selection of potential degradation locations. As the primary interest in RI-ISI is in the risk ranking of the welds, the absolute quantitative results are of less importance than the relative results, which are not sensitive for eventual conservative assumptions of the model. One advantage of the PFM model is also the explicit treatment of inspection reliability, which enables sensitivity studies with different inspection policies. It should be mentioned that the statistical analysis procedure has also been completed with a Markov model to allow for explicit modelling of inspection reliability (Lydell 2001, see e.g. Fleming & Mikschl 1998).

It is very important to identify and clearly document the major uncertainties and assumptions behind the models and their results. The same recommendation applies for the role of expert judgement both inside the models and in the use of the models. Although both approaches include large uncertainties and also may need further development, they are important steps towards better quantification of pipe break frequencies.

The further development of both PFM and statistical estimation approaches and especially the discussions between PSA and material experts should be strongly encouraged. As an example, we would recommend the material and structural engineer's expertise to be included in the estimation of ruptures, especially when there is no experience from them. This could be easily incorporated in the statistical model, as it uses a Bayesian approach in the estimation of the probability of a rupture given a leak.

7 References

Andersson, K. 1997. Strategies for reactor safety. Final report of the Nordic Nuclear Safety Research Project RAK-1. NKS(97)FR1.

Bergman, M. 1997. PIFRAP user's manual, version 1.0, SAQ FoU-Report 97/07.

Bergman, M., Brickstad, B. & Nilsson, F. 1997. A procedure for estimation of pipe break probalilities due to IGSCC. SAQ/FoU-Report 97/06.

Brickstad, B. 1999. The use of risk based methods for establishing ISI-priorities for piping components at Oskarshamn 1 nuclear power station. SAQ/FoU-Report 99/05, 83 p.

Brickstad, B. 2001. Evaluation of pipe failure probabilities for Barsebäck unit 1. Report No. 10259800-1,21 p.

Brickstad, B. 2002. Private communication.

Brickstad, B. & Josefson, B. L. 1998. A parametric study of residual stresses in multi-pass butt-welded stainless steel pipes. Int. J. of Pressure Vessels and Piping 75 (1998) 11-25.

Brickstad, B. & Zang, W. 2001. NURBIT nuclear RBI analysis tool - a software for risk management of nuclear components. DNV Report 01334900-1.

Fleming, K. & Mikschl, T. 1998. Application of Markovian technique to modeling influences of inspection on pipe rupture frequencies. In: Mosleh, A. & Bari, R. (eds.), probabilistic safety assessment and management. Proceedings of the PSAM4 conference. Pp. 463-468.

Harris, D.O. & Dedhia, D. 1998. WinPRAISE 98 PRAISE Code in Windows. Technical Report TR-98-4-1 (Ver. 4.24). Engineering Mechanics Technology.

Lydell, B. 1999. Failure rates in Barsebäck-1 reactor coolant pressure boundary piping An application of a piping failure database. SKI Report 98:30

Lydell, B. 2001. Private communication, comments to the draft report.

Wilkowski, G., Tregoning, R., Scott, P. & Rudland, D. 2002. Status of efforts to evaluate LOCA frequency estimates using combined PRA and PFM appraoches. Stuttgart: 28th. MPA-Seminar, Paper 14. 19 p.

Barsebäck: PSA_ver2_database

Description of the input data for the PIFRAP program.

Table 1. Geometrical input data.

Param.	Description	Probability
D	Outer diameter of pipe	Deterministic
t	Wall Thickness	Deterministic
a_0	Initial crack depth	Fixed (1 mm)
$1/\lambda_0$	Expected crack length at inner surface [%]	Random, based on Swedish data

Table 2. Service load data, contributing to the crack propagation by IGSCC.

Param.	Description	Treatment
p	Internal pressure	Deterministic
P_m	Primary membrane stress [1)]	Deterministic
P_b	Primary bending stress	Deterministic
P_e	Thermal expansion bending stress	Deterministic
$\sigma(u)$	Through-thickness distribution of welding residual stress	Deterministic

[1)] Mainly due to internal pressure
[2)] Global bending stress amplitude in case of high cycle vibrations

Table 3. Complementary failure load data.

Param.	Description	Treatment
p	Internal pressure	Probability of occurrence: f_{load}
P_m	Primary membrane stress	Probability of occurrence: f_{load}
P_b	Primary bending stress	Probability of occurrence: f_{load}
P_e	Expansion stress	Probability of occurrence: f_{load}
$\sigma(u)$	Through-thickness distribution of welding residual stresses and thermal stress	Probability of occurrence: f_{load}

Table 4. Material properties, to be given at the actual temperature during service load. Used also for the complementary failure load.

Param.	**Description**	**Treatment**
σ_y	Yield strength	Deterministic
σ_u	Ultimate tensile strength	Deterministic
J_{1C}	Initiation fracture toughness[1)]	Deterministic
E	Elastic modulus	Deterministic
ν	Poissons ratio	Deterministic
ΔK_a	Vibration fatigue threshold value	Deterministic

[1)] To account for some stable crack growth, J_R-value corresponding to some ductile crack growth can be applied. For unirradiated austenitic stainless steels and nickel base alloys as well as their associated welds, J_R-value corresponding to $\Delta a = 2$ mm is recommended.

Table 5. Subcritical crack growth data, unit system [MPa, mm, s].

Param.	**Description**	**Treatment**
C_0	Parameter of crack growth law [1)]	Deterministic
n	Parameter of crack growth law [1)]	Deterministic
C_1	Parameter of crack growth law [1)]	Deterministic

[1)] The crack growth law is defined as $\frac{da}{dt} = C_0(K_I - C_I)^n$

Table 6. Parameters of mass leakage rate calculation with SQUIRT[1)].

Param.	**Description** (and recommended value)	**Unit**	**Treatment**
μ	Surface roughness (0.089	mm	Deterministic
PLC	Path loss coefficient (28.2)	velocity heads/ mm	Deterministic
Cd	Discharge coefficient (0.95)	-	Deterministic
p_{ext}	External pressure (0.1)	MPa	Deterministic
T_{fluid}	Fluid temperature (at service load)	°C (?)	Deterministic
d	Leak rate detection limit	kg/s	Deterministic

[1)] The calculated leak rate is assumed to be normally distributed for varying crack morphology parameters. The deterministic value calculated by SQUIRT is assumed to be the mean value (Bergman et. al. 1997).

Table 7. Inspection: probability of crack detection. Probability of not detecting a crack at an inspection is assumed to be $p_{nd} = 1 - \Phi\left[C_1 + C_2 \ln(a/t)\right]$. ϕ *is normalised Gaussian distribution.*

Param.	**Description**	**Treatment**
C_1	Parameter of probability function[1)]	Deterministic
C_2	Parameter of probability function[2)]	Deterministic
Δt	Inspection interval	Deterministic
T_{exp}	Expected total time in service	Deterministic
T_{ope}	Time in service since start of operation	Deterministic

[1)] Values for poor, good and advanced team: 0.240, 1.526 and 3.630.
[2)] Values for poor, good and advanced team: 1.485, 0.533 and 1.106.

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Author(s)	Kaisa Simola, Urho Pulkkinen, Heli Talja, Arja Saarenheimo & Päivi Karjalainen-Roikonen
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Abstract

The report describes the comparative study of two approaches to estimate pipe leak and rupture frequencies for piping. One method is based on a probabilistic fracture mechanistic (PFM) model while the other one is based on statistical estimation of rupture frequencies from a large database. In order to be able to compare the approaches and their results, the rupture frequencies of some selected welds have been estimated using both of these methods. This paper highlights the differences both in methods, input data, need and use of plant specific information and need of expert judgement. The study focuses on one specific degradation mechanism, namely the intergranular stress corrosion cracking (IGSCC). This is the major degradation mechanism in old stainless steel piping in BWR environment, and its growth is influenced by material properties, stresses and water chemistry.

Key words: Probabilistic fracture mechanics, IGSCC, risk-informed in-service inspections, pipe break frequency

Available on request from the NKS Secretariat, P.O.Box 30, DK-4000 Roskilde, Denmark.
Phone (+45) 4677 4045, fax (+45) 4677 4046, e-mail nks@catscience.dk, www.nks.org.