IMPROVED APPROACH FOR ESTIMATING LEAK AND BREAK FREQUENCIES OF PIPING SYSTEMS IN PROBABILISTIC SAFETY ASSESSMENT

H.-P. Berg, R. Gersinska
•
Bundesamt für Strahlenschutz, Salzgitter, Germany

e-mail: hberg@bfs.de

J. Sievers
•
Gesellschaft für Anlagen- und Reaktorsicherheit, Köln, Germany

ABSTRACT

The estimation of leak and break frequencies in piping systems is part of the probabilistic safety assessment of technical plants. In this paper, the statistical method based on the evaluation of the German operational experience for piping systems with different diameters is described because an earlier estimation has been updated and extended introducing new methodical aspects and data. Major point is the inclusion of structure reliability models based on fracture mechanics calculation procedures. As an example of application the statistical estimation method for leak and break frequencies of piping systems with a nominal diameter of 50 mm (the volume control system of a German pressurized water reactor) was updated. Moreover, the evaluation of the operational experience was extended to 341 years with respect to cracks, leaks and breaks in the volume control system of German pressurized water reactors (PWR). Using the actual data base, new calculations of leak and break frequencies have been performed and the results have been compared with the previous values.

1 INTRODUCTION

In general, the likelihood of leaks of piping systems is of importance for the safety of process plants like chemical plants, both onshore and offshore industries and for nuclear power plants.

In case of all kind of process plants, leak and break frequencies are an input to any probabilistic safety assessment (PSA) of the process plant, usually called quantitative risk assessment (QRA) for these types of plants.

As explained in (Spuge 2005), standardized leak frequencies have been developed, based on recent data from offshore process, for different types of process equipment to ensure that consistent frequencies are available for any equipment type and hole size.

In the nuclear field, a report has been recently issued by the US regulatory body (U.S. NRC 2008) describing the development of leak frequency estimates, in particular for the loss-of-coolant accidents (LOCA), as a function of effective break size and operating time through the end of the plant license-renewal period. The estimates were based on an expert elicitation process consolidating operating experience and insights from probabilistic fracture mechanics studies with knowledge about the plant design, operation history and material performance during operation.

The elicitation required that each member of a group of international experts assessed qualitatively and quantitatively the important factors contributing to LOCA frequencies and quantify their uncertainties. Each member estimated the leak frequencies based on four reference cases.

The expert estimation for different systems and components was achieved by a factor relative to one reference case of his choice. After estimation each expert was asked in an interview for the rationale behind the given factor. A statistical evaluation of all answers was performed. Finally, the individual estimates were aggregated to obtain group estimates. Leak frequencies were provided for mean, median, 5th and 95th percentiles.

Compared to earlier evaluations for pressurized water reactors, the results of the elicitation are generally in good agreement, only for medium LOCA sizes (30 – 100 cm^2) the results of the elicitation process are significantly higher because of the high potential of the damage mechanism “primary water stress corrosion cracking”.

In Germany, in accordance with § 19a of the national Atomic Energy Act a regulatory guideline exists for performing the probabilistic safety assessment (PSA) in the context of comprehensive safety reviews.

In addition, the Working Group „Probabilistic Safety Assessment for Nuclear Power Plants", leaded by BfS, had compiled two technical documents on methods and data for PSA (FAK PSA 2005 a), (FAK PSA 2005 b) which are usually updated after about five years. These documents also provide guidance how to deal with leak and break frequencies of pipes within a PSA.

This paper describes the statistical method, meanwhile updated, by including structure reliability models and using the recently extended database. Substantial relevant aspects were identified with reference to the determination of leak and break frequencies and proposals are provided for an update based on the current state-of-the-art.

2 DETERMINATION OF LEAK FREQUENCIES

2.1 Basic information

A leak in consequence of the failure of a piping can be caused by a wall-penetrating crack, by a break or by leaks at a solvable connection. According to experience a piping failure arises rarely at unimpaired ranges of the piping, but obviously more frequently on leak-relevant positions.

Typical examples for these positions are flanges, connections to components, elbow unions, reductions, reinforcement for pipe brackets, banks of tubes in heat exchangers and dissimilar welding seams.

Within such ranges stress enhancements exist, caused by changes in stiffness, inhomogeneous temperatures and flow within feeding ranges as well as by external additional loads, as e.g. bending moments or forces. Damages can, then, develop due to irregularities of the surface or by small flaws resulting from manufacturing in welding seams, which are in these ranges and which were not found either during the manufacture quality control process or were not evaluated as relevant findings.

Leak-relevant positions can be also in ranges which are affected by local corrosion-conditioned influences (e.g. enrichments, deposits, condensation, protective layer disturbances).

The following damage mechanisms are to be regarded at least:

- cracking due to thermal or mechanical fatigue or corrosion (e.g. stress corrosion cracking),
- material weakening by (planar) corrosion or erosion,
- overload (e.g. by internal pressure, temperature, malfunctioning of supports and shock absorbers, water hammer, condensation impact, ignition of radiolysis gas),
- assembly and maintenance error,
- external effects, e.g. from assembly and transport operations, earthquake.

Which types of damage causes are to be considered with the examined system depend particularly on the material, the dimensions, the medium and the operating conditions.

For example, mechanical oscillations can occur particularly with small nominal sizes, while thermal alternating loads, e.g. as a consequence of leaks of shutoff devices, are of higher importance with larger nominal sizes.

Influences from the commissioning phase or from longer shutdown periods can increase the frequency of certain damage causes, as e.g. from assembly and maintenance faults or due to corrosion mechanisms. In that context, also corrosion releasing aids during assembling and maintenance (e.g. chloride contamination by tapes and foils or lubricants) has to be considered.

Occurrence frequencies of leaks can be determined by a statistic evaluation of the operational experience. For the definition of the population to be included into this evaluation it is necessary to evaluate the comparability of the systems, materials, water chemistry, manufacture conditions and the quality and completeness of the experience feedback from the plants.

If possible statistics should be provided regarding the number of the leak-relevant positions of a system and/or a nominal size class. For the determination of the frequency of an event, the use of a statistic on precursor events is better than a zero-error statistic for the event (e.g. break). The correlation between the frequency of the precursor events and the event which has to be evaluated is to be estimated then by the damage mechanisms and the potential for the initial event.

In this context leaks due to wall-penetrating cracks should be considered to determine break frequencies.

No precursor events of a leak within certain systems with very high quality standard are to be expected.

This, at present, essentially applies to the main piping of the pressurized and boiling water reactors, which are laid out on the German basic safety principles. In such cases it is possible to determine extremely small leak frequencies (e.g. $< 10^{-7}$/a), which are clearly under the frequencies calculated from a zero-error statistics.

Such analyses were accomplished by different organisations with the help of probabilistic fracture-mechanics methods with comparable results. Usually for such piping a break preclusion is assumed.

For a break exclusion beside the concept of basis safety as laid down in documents of the German Reactor Safety Commission (RSK 1979), (RSK 1981) – an advisory board for the regulatory body –, a number of further additional measures are necessary for the qualification of piping.

These principle requirements, together with the work procedures for the quality assurance derived from it, were further developed and explained in (Beliczey & Schulz 1990), (Beliczey 1995), (Bieniussa et al. 1995) and (European Commission 2000).

2.2 Classification of the leaks

In the following leaks are defined as a comprehensive term for wall-penetrating cracks or breaks. For the determination of leak frequencies it is important in each case to define the structures the leak frequencies are to be referred.

Possible reference measures are:

– an entire system (e.g. not closable section of the emergency cooling and residual heat removal system TH, or a simply closable section),

– the unit of length of piping of a certain nominal size, or

– a welding seam.

The experience shows that the frequency of leaks depends on the regarded structure (e.g. straight tube, welding seam). Experience has shown that leaks from cracks preferably arise in the vicinity of welding seams.

The frequency of cracks is dominant at welding seams in close proximity to structural discontinuities (e.g. binding of a piping to a component).

These considerations are important for the selection of the leak-relevant design features and positions. Leaks in piping can be classified according to the following criteria:

- system (and/or function of the piping or the part of piping),
- plant condition with occurrence of the leak (e.g. operation conditions),
- design feature and/or position,
- leak size (related to the flow cross section F of the piping), and
- nominal size of the piping.

2.3 Data base

As ideal source for the estimation of the frequency of leaks the system dependent operational experience is considered. With very rare events, however, further considerations must be added. Because, if apart from the findings of the zero-error statistics no further realizations are used, a very conservative statement about the occurrence frequency results.

Independently from the fact whether on a system or on leak-relevant positions referred leak frequencies are to be determined, there is always the difficulty to obtain the knowledge of the structure of the system or of the number of the leak-relevant positions in all statistically seized plants.

For example, the determination of the leak-relevant positions can take place after studying the appropriate flow chart with the help of a plant inspection. In rare cases one will be able to determine these positions alone from the flow plans and piping isometries.

Due to the generally missing detailed knowledge of the plants considered in the statistics it is accepted that the number of the leak-relevant positions is in a certain system section of the plant which can be examined equal to the average value of this number in all plants considered for the statistics.

From this principle it can only be deviated when it is known from the plant under consideration that there is a substantially deviation concerning the number of certain positions from the average.

Thus, for example for the not-closable part of systems such as emergency cooling and residual heat removal system (TH) or volume control system two leak-relevant positions are assumed: one at the connection with the main cooling line (HKL), one at the isolation valve.

If a system section is very safety-relevant, one can be sure that the leak occurrences of all sizes were described in the usual operational experience documents.

Therefore, one will be able to consult the international operational experience (for example from USA, Japan, France) for larger parts than a nominal diameter of DN 15 mm, e.g. for breaks of not closable piping in the main cooling cycle.

As far as possible, it is reasonable to make use of common international databases such as the OPDE database (Lydell & Riznic 2008). Current results from this database show that leak frequencies dominate the whole piping failure frequency.

However, as a general principle, only those plants with similar materials should be considered. A restriction on the zero-error statistics in the not closable sections of German nuclear power plants would be too conservative.

2.4 Methodology for the determination of leak and break frequencies

In the following, the applied methodology for the determination of leak and break frequencies by means of evaluating the operating experience and the used statistic procedures is explained.

For the nominal diameter (given in mm) range 50 ≤ DN ≤ 150 the frequency of a wall-penetrating crack (leak) is given through the so-called Thomas formula (Thomas 1981):

$$\lambda_L = C \cdot \left(L_D \cdot D\right) / t_D^x \tag{1}$$

L_D Number of the leak-relevant positions,
D=DN Nominal diameter,
t_D Wall thickness of the piping with diameter D,
x Exponent with values within the range 2 to 3.

$$C = \frac{\sum_{D=50}^{D=150} N_{L,D}}{\sum_{D=50}^{D=150} \left(L_D \cdot D / t_D^x\right) \cdot T_D} \tag{2}$$

T_D Actual operation time,
$N_{L,D}$ Number of the arisen leaks (diameter D)

The constant C includes the operational experience in terms of number of leaks in piping with different nominal diameter forming a population, in relation to the operation time, to broaden the statistical basis for the leak frequency of the respective nominal diameter DN considered.

In the nominal diameter range 25 ≤ DN ≤ 250 the break frequency is estimated according to:

$$\lambda_B = \lambda_L \cdot 2{,}5 / DN \tag{3}$$

The evaluation of austenitic piping under fatigue load in (Beliczey & Schulz 1990) serves as basis. For DN < 50 as far as possible a direct statistic evaluation of leak and of break occurrences takes place. For primary cycle systems with 150 < DN < 250 the leak frequency corresponds to the same as for DN 150.

For primary cycle systems with DN ≥ 250, without the main cooling line, during basis-safety principle the following statements are valid:

The break frequency per leak relevant position λ_B is smaller than 10^{-7}/a for small systems ($L_D < 10$). λ_B is smaller than 10^{-8}/a for large systems. For the main cooling line, the break frequency λ_B is small ($<10^{-7}$/a) compared to the entire line.

In order to consider the uncertainties during the definition of certain input data, distributions are to be considered for these certain input values which determine the range for the uncertainty of the respective result.

2.5 Example of use for determination of leak and break frequencies by means of operating evaluation and statistic procedures

As an example the determination of the frequency of a break in the volume control system (TA) is described for a German pressurized water reactors (PWR).

In a first step, an adjustment of the example discussed in the existing document on PSA data (FAK PSA 2005) has been performed by a new evaluation of the operational experience in recent years.

The operating experience was extended from so far 191 years (until 1995) on to now 341 years (until 2006). With these updated data the leak and break frequencies were calculated new.

Table 1 gives an overview of the number of leak-relevant positions of the TA-system for 14 PWR divided into three groups A, B and C with structurally similar plants broken down into the operating conditions hot/cold.

Group of A covers 5 plants, B 8 plants and C is represented by only one plant. The range of the operational experience until 2006 amounts to 151 years (A), 153 years (B) and 37 years (C).

Table 2 shows the results of the new evaluation of the operational experience for the volume control system of German PWR. The reference time amounted to so far 191 years and with the new data now 341 years.

Table 1. Overview of the number of leak-relevant positions of the TA-system

DN [mm]	**A cold**	**A hot**	**B cold**	**B hot**	**C cold**	**C hot**
100	10	7	11	1	-	-
80	50	2	70	36	3	-
50	23	20	36	36	88	30
25	43	15	92	45	33	3
15	62	4	119	20	125	24

Based on the methodology described in this paper the break frequency per leak relevant position in the piping range of the nominal diameter DN 50 was calculated.

Table 3 shows the results of the new calculation of the example compared with the results given in (FAK PSA 2005).

This comparison shows that the new calculated frequencies have not changed significantly due to the evaluation of extended operational experience.

This result is exemplary and might not be typical for the behaviour of piping systems. Due to ageing effects, the influence of in-service-inspections, repairs performed and replacing of components the change in the number of leaks in relation to the operation time might lead to changes in the leak frequencies resulting from operational experience.

Table 2. Results of the new evaluation of the operational experience for the volume control system.

DN [mm]	**Number of events (until 2006)**	**Number of leaks as break precursor in (FAK PSA 2005)**	**Number of leaks as break precursor (new evaluation)**
15	6	2	4
25	11	6	6
50	8	2	7
80	3	1	2
100	5	-	1
Sum	33	11	20

Table 3. Comparison of the new calculation of the example with the results given in (FAK PSA 2005).

Measures for the break frequency distribution λ_B for DN 50 [mm]	**Former example in reference (FAK PSA 2005)**	**New calculation**
$\lambda_{B,5}$ (5%-quantile)	$2\cdot10^{-6}$	$4\cdot10^{-6}$
$\lambda_{B,50}$ (50%-quantile)	$7\cdot10^{-6}$	$1\cdot10^{-5}$
$\lambda_{B,95}$ (95%-quantile)	$3\cdot10^{-5}$	$4\cdot10^{-5}$
Expected value	$1\cdot10^{-5}$	$1\cdot10^{-5}$

2.6 Disadvantages of the methodology

Although the method as described is quite successful, there are some disadvantages and limits which should be mentioned:

- the specification of leak-relevant positions is very complex and not well-defined,
- the interpretation of the leaks as break precursor requires a large experience in fracture-mechanics and knowledge about the system,
- the result within a system section can be differentiated not further (e.g. regarding possible different loads for different positions).

These disadvantages are the reason for the coupling of the methodology with structural reliability models.

2.7 Structural reliability models

The described methodology which is based on statistics is not suitable for possible leak-relevant special characteristics (e.g. concerning the loading of pipes). For that purpose the use of structural reliability models would be necessary.

With the structural reliability programmes today it is possible to calculate the quantitative probabilities of leaks and breaks dependent on the position (e.g. for a certain welding seam) for certain damage mechanisms.

One proceeds as follows. For the substantial input measures (e. g. geometrical data, parameters characterising material properties, cracks, loading) distributions are identified. From this, for example, by applying Monte Carlo procedures a multiplicity of parameter combinations is randomly determined. With the help of fracture-mechanics procedures the growth of an initial crack for the respective parameter combination is determined. Altogether one receives a prognosis of the damage development of certain defect geometries under the loads which are to be expected.

Sections of a system can be differentiated regarding their failure relevance for the determination of the time and position dependent probability of leak by the employment of the structural reliability programmes. The probabilistic computation models are well suitable for the calculation of leak and break probabilities of piping and to determine trends quantitatively concerning the change of influence parameters.

Restrictions are seen in particular concerning the accuracy of absolute leak and break probabilities. The results depend to some extent strongly on the uncertainties during the definition of distributions for the relevant input parameters. In this context, parameters such as crack geometry, expected loads and those for the characterisation of the damage mechanisms play a substantial role.

A systematic comparison of different structural reliability programmes was made in the framework of (NURBIM 2004). Besides one US, English and Swedish programme, the structural reliability programme PROST developed by GRS (Grebner et al. 2004) participated in this comparison. The evaluation of the results shows that all programmes achieve the expected trends in the probability of leaks with variation of the input parameters. The probabilities of leak of the different codes agree well for the piping geometries considered.

Most of the structural reliability programmes available provide possibilities to include the effects of in-service-inspections and repair measures in the calculations on leak and break probabilities. A matter of further research might be the inclusion of time depending effects (e.g. due to ageing) in the input data of the structural reliability programmes.

3 INTEGRITY CONCEPT FOR PIPING SYSTEMS

As described above, methods based on statistics and structural reliability models are applied to get information on frequencies of possible leaks or breaks. Technically, precautionary measures are taken to exclude failures of safety relevant systems.

In Germany, a so-called integrity concept is applied (Hoffmann et al. 2007), in particular to exclude catastrophic failures of safety relevant pressure retaining components in nuclear power plants during operation.

This integrity concept is based on the requirements of assured basic safety characteristics such as design, construction, material properties and manufacturing. Complementary instruments which are implemented are the principle of multiple checking, worst-case principle, comprehensive plant monitoring, e.g. in the frame of ageing programmes, as well as the principle of verification of the actual quality status. This verification is performed on a continuous basis and, in addition, checked during the comprehensive safety review every ten years as part of the regulatory surveillance process.

Fracture mechanics safety analysis with postulated defect sizes as well as the experimental results of load behaviour to be expected are essential parts of the integrity concept. The measures determined in this way shall ensure that no major deviations from design values occur which has to be confirmed by periodic in-service inspections.

4 RISK-INFORMED IN-SERVICE INSPECTION

As explained above, the overall aim of the programme for in-service inspection of the piping at a nuclear power plant is to inspect the piping and identify areas of degradation that can be repaired before a failure occurs. The programme of inspections that is carried out has been based on a traditional deterministic approach and engineering judgement.

The use of risk informed in-service inspection methodologies in planning piping inspections in nuclear power plants is becoming mor and more common. The aim of the risk informed approach is to integrate service experiences, plant and operating conditions, other deterministic information and risk insights and to use the insights provided by the PSA to revise the programme of inspections that are carried out (in terms of the frequency of inspections, methods used, sample size, etc.), see for example (Berg 2009). As a consequence, the approach focuses on the segments of the pipe work that have the highest risk significance and reduces the inspections carried out on those with a low risk significance.

One recent approach (Männistö et al. 2009) is a fully quantitative risk informed in-service inspection methodology combining probabilistic fracture mechanics and discrete time Markov models.

Several different approaches have been developed for carrying out risk informed in-service inspection (European Commission 2005). Although the main steps are similar, the different methods and procedures differ considerably from each other in the way the evaluation and the selection of inspection sites are performed. All known risk informed in-service inspection methodologies are restricted to piping (NEA/OECD 2007).

Insights from the level 1 PSA should be used as one of the inputs in determining the piping segments to be addressed by the risk-informed in-service inspection project, the risk significance of the segments of piping being addressed, the target probabilities for the piping segments that are inspected and the changes in the risk which result from changes to the in-service inspection programme.

For piping failures leading to initiating events, the PSA should be used to determine the conditional core damage probability. For piping failures leading to the failure of standby systems or failure of systems on demand, the PSA should be used to calculate the conditional core damage frequency.

However, the piping failures that lead to the unavailability or failure on demand of safety systems are not generally included in the PSA model since the contribution to the failure probability of safety systems from failure of the pipe work is negligible in comparison to that from a failure of active components.

The rigorous way of determining the risk significance of all the segments of pipe work included in the risk-informed in-service inspection project would be to revise the PSA model to include these pipe work segments explicitly so that the core damage frequency and conditional core damage probability could be determined directly. This approach has been used in some countries.

When the revised in-service inspection programme has been defined, the PSA should be used to determine the risk insights needed for comparison against the decision criteria or guidelines used to assess the acceptability of the change in the in-service inspection programme.

This can be done by estimating what the change in the initiating event frequency or the component failure probability would be as a result of changes in the in-service inspection programme and rerunning the PSA or by carrying out sensitivity studies. In this process, the associated PSA limitations in terms of modelling details, scope, etc. should be recognized and taken into account.

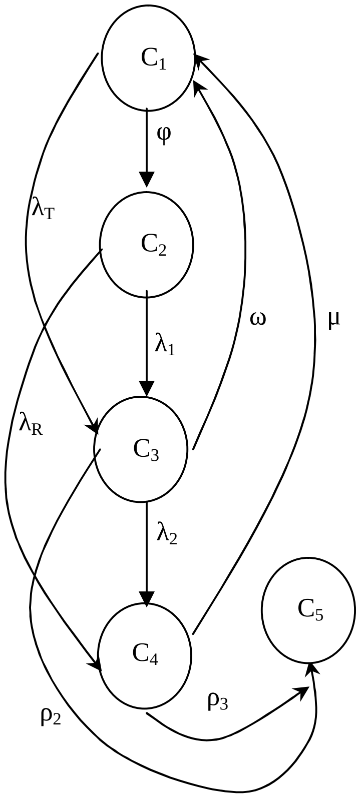
5 MARKOV MODELS FOR ESTIMATING PIPE FAILURES

As explained above, there are several different approaches to estimate pipe leak and break frequencies. One is based on statistical estimation from large databases and the other one on probabilistic fracture mechanics. In (Simola et al. 2004), the purposes of the approaches and the differences in modeling and data use are highlighted. The results of the break frequencies obtained by the two approaches are quite different, but one approach does not give systematically higher values than the other one.

It should be mentioned that the statistical analysis approach has also been developed in using a Markov model to allow an explicit modeling with respect to risk-informed in-service inspection strategies for piping systems in nuclear power plants (Fleming 2004).

The model described in (Fleming 2004) contains four pipe element states where one of it is a success state and may have the capability to model the main known pipe failure mechanisms. These failure mechanisms include damage mechanisms that operate in pipe base metal (e.g. flow accelerated corrosion), those that act on welds or in the heat affected zone near welds (e.g. thermal fatigue), combinations of mechanisms involving wall thinning and crack propagation, damage unrelated mechanisms such as those associated with severe loading such as water hammer and overpressure, and failures due to various combinations of these failure mechanisms.

However, the most general Markov model as a further development of (Fleming 2004) that has the capability to model at least all known pipe failure mechanisms is shown in Figure 1. It includes a further pipe element state compared with (Fleming 2004).



Pipe Element States

C_1 –Success, no detectable damage state
C_2 – Category 2 events, welding failures
C_3 – Category 3 events, part-cracks, full-cracks, reportable events
C_4 - Category 4 events, through-wall leaks
C_5 – Rupture or severe events

State Transition Rates
φ – category C_2 events occurrence rate
λ_1 – part-crack failure rate, given welding failures
λ_2 – leak failure rate, given part-crack failures
λ_R – leak failure rate given welding failures
λ_T - part-crack failure rate given success state
ρ_3 – rupture failure rate given leaks
ρ_2 – rupture failure rate given part-crack failures
ω – repair rate of part crack failures
μ – repair rate of leaking failures

Figure 1. Five state Markov model for all pipe failure mechanisms

The only ‘success state’ in the Markov model shown in Figure 1 is C_1, the others states are ‘failure states’ of different failure types with different severity of consequences.

When the solutions to the respective differential equations are solved, the time dependent probabilities of the piping component occupying each state can be determined.

Under the assumption that all the transition rates are constant, the Markov model equations consist of a set of coupled linear differential equations with constant coefficients. These equations can be solved analytically or numerically.

The appropriate reliability metric of the Markov model that quantifies the time dependent pipe rupture frequency is the system failure rate or hazard rate, as defined in the following.

To determine the system failure rate or hazard rate, one way is to first determine the system reliability function for the model and then to derive the hazard rate as a function of the reliability function according to the definition of the hazard rate as explained below. One approach is to focus on pipe ruptures and seek to estimate pipe rupture frequencies. Thus, instead of the definition of C_1 as the only 'success state', one can declare any state except that for rupture a 'success state'. This means that only the rupture state is a 'failure state'.

Using this concept, the reliability function for the Markov model, r{t}, is then given by

$$r\{t\} = 1 - C_5\{t\} = C_1\{t\} + C_2\{t\} + C_3\{t\} + C_4\{t\} \tag{4}$$

Under the above mentioned boundary condition, one can define from equation (4) the hazard rate for pipe ruptures (C_5), h{t}, as

$$h\{t\} = -\frac{1}{r\{t\}}\frac{dr\{t]}{dt} = \frac{1}{1 - C_5\{t\}}\frac{dC_5\{t\}}{dt} \tag{5}$$

The hazard rate, h{t}, is the time dependent frequency of pipe ruptures. The time dependent form of this rate strongly depends on the boundary conditions of the model and an asymptotic rate, which is a function of the parameters (transition rates) of the model.

6 CONCLUDING REMARKS

This paper explains the updated the method for the determination of leak and break frequencies in piping of German nuclear power plants which is proposed to be included in the revision of the documents on methods and data volume for the probabilistic safety assessment. The statistic methodology is based on the evaluation of the updated German operational experience for piping of different nominal diameters.

A direct generic statistical evaluation of the operating experience is only possible for small diameter piping (DN<50).

For larger pipings an estimation of leak frequencies needs additional assumptions like expert judgement and/or precursor evaluation, the consideration of equivalent systems or the results of trend analyses, for example performed in the frame of comprehensive safety reviews.

A detailed evaluation, e.g. of primary circuit leak frequencies, in a specific plant is time consuming and plant-specific data may be spare. In that case, it is recommended to use available generic frequency data. However, it has to be shown that the plant under consideration – a process plant or a nuclear power plant – is comparable to the plant where the generic data set results from.

This paper provided, in addition, an example for using the statistical method based on the evaluation of the German operating experience with nuclear power plants. The determination of the break frequency in the volume control system is described by expanding the operational experience from originally approx. 191 reactor years to 341 reactor years. Under these updated boundary conditions new computations of the leak and break frequencies were accomplished. The results show that the calculated break frequencies have not changed significantly due to the evaluation of extended operational experience compared with earlier results.

A further development of the methodology took place via an inclusion of structural reliability models based on fracture-mechanics computation methods.

There are several challenges in evaluating pipe failure probabilities and also in analyzing the effectiveness of inspections.

Moreover, pipe failure databases have been collected internationally, but the data is usually collected from nuclear power plants under a certain inspection programme which makes it difficult to compare different inspection programmes.

Because estimates of failure rates for nuclear power plant piping systems are important inputs to PSA and to risk-informed applications such as the approach of risk-informed in-service inspection as described above, the treatment of uncertainties is an important issue. Sources of uncertainty include failure data reporting issues, scarcity of data, inappropriate characterization of component populations as well as uncertainties about the physical characteristics of the failure mechanisms and root causes. A possible methodology for quantifying these uncertainties is provided in (Fleming & Lydell 2004).

As shortly mentioned, a combined method based on the application of probabilistic fracture mechanics and a Markov model has been developed as well as a statistical analysis approach also using a Markov model; however, it might be more likely to use semi-Markov processes for that purposes.

REFERENCES

Beliczey, S. (1995). *Grundlegende statistische Methoden.* GRS-Fachseminar zu „Ermittlung der Häufigkeiten von Lecks und Brücken in druckführenden Systemen für PSA“, Köln, 18.-20. September 1995 (published in German).

Beliczey, S. & Schulz, H. (1990). Comments on probabilities of leaks and breaks of safety-related piping in PWR plants. *Int. J. Pres. Ves. & Piping* Vol. 43, 219-227.

Berg, H.P. (2009). Overview on the different applications of probabilistic safety assessment for nuclear power plants. *Kerntechnik 74*, No 3, 106-110.

Bieniussa, K., Schulz, H., Goetsch, D., & Jalouneix, J. (1995). Integrity of the Reactor Coolant Boundary of the European Pressurized Water Reactor - Requirements for the Application of the Break Precluding Concept to the Main Coolant Lines, *Proceedings of the Seminar on Leak-Before-Break in Reactor Piping and Vessels*, Lyon. France, October 9-11, 1995. NUREG/CP-0155.

European Commission. (2000). *Final Report: Comparison of National Leak-Before-Break Procedures and Practices - Summary of Results and Potential for Greater Harmonisation.* Revision 2, EU Study Contract B7-5200/97/000782/ MAR/C2 of DG XI, April 2000.

European Commission. (2005). *Report on the Regulatory Experience of Risk-informed In-Service Inspection of Nuclear Power Plant Components and Common Views.* EUR 21320 EN, August 2004, Luxembourg, 2005.

Facharbeitskreis Probabilistische Sicherheitsanalyse für Kernkraftwerke (FAK PSA) (2005 a). *Methoden zur probabilistischen Sicherheitsanalyse für Kernkraftwerke, Stand: August 2005.* BfS-SCHR-37/05, Salzgitter, October 2005 (published in German).

Facharbeitskreis Probabilistische Sicherheitsanalyse für Kernkraftwerke (FAK PSA) (2005 b). *Daten zur probabilistischen Sicherheitsanalyse für Kernkraftwerke, Stand: August 2005.* BfS-SCHR-38/05, Salzgitter, October 2005 (published in German).

Fleming, K. (2004) Markov models for evaluating risk-informed in-service inspection strategies for nuclear power plant piping systems. *Reliability Engineering & Safety System* 83, 27-45.

Fleming, K. & Lydell, B. (2004). Database development and uncertainty treatment for estimating pipe failure rates and rupture frequencies. *Reliability Engineering & Safety System* 86, 227-246.

Grebner, H., Schimpfke, T., Peschke, J. & Sievers, J. (2004). *Weiterentwicklung der struktur-mechanischen Analysemethodik zur Bestimmung der Strukturzuverlässigkeit passiver Komponenten.* GRS-A-3236 (published in German).

Hoffmann, H. et al. (2007). Integrity concept for piping systems with corresponding leak and break postulates in German nuclear power plants. *VGB Power Tech* 7, 3-16.

Lydell, B. & Riznic, J. (2008). OPDE – the international pipe failure data exchange project. *Nuclear Engineering and Design* 238, 8, 2115-2123.

Männistö, I., Cronvall, O. & Simola, K. (2009). A Quantitative Method for RI-ISI Assessment, *Proceedings of the 20th International Conference on Structural Mechanics in Reactor Technology (SMiRT 20)*, Espoo, Finland, August 2009, Paper 1975 (on CD).

Nuclear Energy Agency/OECD. (2007). *Use and Development of Probabilistic Safety Assessment*, NEA/CSNI/R (2007) 12, November 2007.

NURBIM (2004). *Nuclear Risk-Based Inspection Methodology for Passive Components (NURBIM), 2004*. EU Contract FIKS-CT-2001-00172, Final report.

Reaktor-Sicherheitskommission (RSK) (1979). *2. Anhang zu den RSK-Leitlinien für Druckwasserreaktoren 1979. (2. Ausgabe vom 24. Jan. 1979) Kapitel 4.2, Rahmenspezifikation Basissicherheit von druckführenden Komponenten, Stand 25.04.1979.*

Reaktor-Sicherheitskommission (RSK) (1981). *RSK-Leitlinien für Druckwasserreaktoren*. Ausgabe 10/1981.

Schulz, H. (1995). The Evolution of the Break Preclusion Concept for Nuclear Power Plants in Germany. *Proceedings of the Seminar on Leak-Before-Break in Reactor Piping and Vessels*. Lyon, France, October 9-11, 1995. NUREG/CP-0155.

Simola, K. et al. (2004). Comparison of approaches for estimating pipe rupture frequencies for risk-informed in-service inspections. *Reliability Engineering & Safety System* 84, 65-74.

Spuge, J. (2005). New generic leak frequencies for process equipment. *Process Safety Progress* 24, No 4, 249-257.

Thomas, H. M. (1981). Pipe and Vessel Failure Probability. *Rel. Engineering* 2., 83-124.

U.S. Nuclear Regulatory Commission (2008). *Estimating loss-of-coolant accident (LOCA) frequencies through the elicitation process, main report.* NUREG-1829, Vol. 1, April 2008.