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Studies on the effect of flaw detection probability assumptions on risk reduction at inspection

Kaisa Simola (1), Otso Cronvall (1), Ilkka Männistö (1)
Jens Gunnars (2) Lars Alverlind (2)
Peter Dillström (2), Luca Gandossi (3)

(1) VTT Technical Research Centre of Finland
(2) Inspecta Technology
(3) European Commission Joint Research Centre

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Abstract

The aim of the project was to study the effect of POD assumptions on failure probability using structural reliability models. The main interest was to investigate whether it is justifiable to use a simplified POD curve e.g. in risk-informed in-service inspection (RI-ISI) studies. The results of the study indicate that the use of a simplified POD curve could be justifiable in RI-ISI applications.
Another aim was to compare various structural reliability calculation approaches for a set of cases. Through benchmarking one can identify differences and similarities between modelling approaches, and provide added confidence on models and identify development needs. Comparing the leakage probabilities calculated by different approaches at the end of plant lifetime (60 years) shows that the results are very similar when inspections are not accounted for. However, when inspections are taken into account the predicted order of magnitude differs. Further studies would be needed to investigate the reasons for the differences. Development needs and plans for the benchmarked structural reliability models are discussed.

Key words

Structural reliability, in-service inspections, NDE, probability of detection

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NKS Secretariat
NKS-776
P.O. Box 49
DK - 4000 Roskilde, Denmark

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

STUDIES ON THE EFFECT OF FLAW DETECTION PROBABILITY ASSUMPTIONS ON RISK REDUCTION AT INSPECTION

REPORT OF THE NKS/PODRIS-PROJECT

Kaisa Simola, Otso Cronvall & Ilkka Männistö	**VTT**
Jens Gunnars, Lars Alverlind & Peter Dillström	**Inspecta**
Luca Gandossi	**JRC Petten**

NKS Nordic Nuclear Safety Research

FOREWORD

This study is part of the Nordic nuclear safety research (NKS) programme. This project was financed by NKS, the Swedish Radiation Safety Authority (SSM), Inspecta Technology, the European Commission's Joint Research Centre (JRC), and the Finnish Nuclear Safety Research Programme SAFIR2010.

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LIST OF ACRONYMS

ASME	American Society of Mechanical Engineers
BWR	Boiling water reactor
CCDP	Conditional core damage probability
CPU	Central processing unit
EC	European Commission
ENIQ	European Network for Inspection and Qualification
FAC	Flow-accelerated corrosion
FORM	First order reliability method
IGSCC	Intergranular stress corrosion cracking
ISI	In-service inspection
JRC	Joint Research Centre
LBB	Leak before break
MSC	Monte-Carlo simulation
LOCA	Loss of coolant accident
NDT	Non-destructive testing
NPP	Nuclear power plant
NURBIM	Nuclear Risk-Based Inspection Methodology
PFM	Probabilistic fracture mechanics
POD	Probability of detection
PSA	Probabilistic safety assessment
PT	Penetrant testing
PWR	Pressurized water reactor
RI-ISI	Risk-informed in-service inspection
RRF	Risk reduction factor
SCC	Stress corrosion cracking
SKI	Swedish Nuclear Power Inspectorate (now SSM)
SKIFS	Swedish Nuclear Power Inspectorate’s regulations
SRM	Structural reliability model
SSM	Swedish Radiation Safety Authority
SSMFS	Swedish Radiation Safety Authority’s regulations (former SKIFS)
TGR	Task Group on Risk
UT	Ultrasonic testing
VTT	Technical Research Centre of Finland

1 INTRODUCTION AND GOALS OF THE STUDY

1.1 Introduction

The risk associated with nuclear power plants is dependent on the possible events of leakage or rupture of piping components, which would threat the pressure retaining capability of the system. In-service inspections (ISI) aim at verifying that defects are not present in components of pressure boundaries or, if there are defects, ensuring that these are detected well before they affect the safe operation of the plant.

Reliability estimates of piping (and other structural components) are needed e.g. in PSA studies, risk-informed ISI applications, and other structural reliability assessments. The reliability of piping components is affected by loads, material and also ISI, since inspection results increase the knowledge of the state of the inspected components.

Risk-informed in-service inspections aim at optimising the inspection programme by taking into account the plant risk analysis results and directing inspections to the risk-significant locations. This will result in a better allocation of resources, in proportion to their importance for safety. Main parts in a risk-informed methodology are consequence assessment, analysis of loads and damage development, and analysis of the inspection efficiency.

When moving from a deterministic to a risk-informed ISI programme, the impact of the programme change upon the risk is evaluated. One important factor influencing the risk evaluation is the inspection reliability, since the risk reduction through inspection is highly related to the inspection reliability.

One approach to quantify the piping failure probabilities is to use probabilistic fracture mechanics (PFM) models. These models can account for the ISI effectiveness and interval, and allow sensitivity studies. A detailed modelling of ISI effectiveness is difficult, since it depends on several factors, and it would be very expensive to produce statistical data to estimate the probability of detection (POD) for various types of flaws. On the other hand, one could question the need of very detailed POD estimates in RI-ISI applications. If sufficient risk reduction can be shown by using simplified (conservative) POD estimates, more complex PODs are not needed.

1.2 Goal of the study

The purpose of this project is to investigate reasonable and practical requirements that should be set for assumptions about the accuracy of how inspection reliability is quantified in terms of probability of detection (POD) curves, from a RI-ISI point of view. This will also help to clarify what POD that needs to be proven at qualification of an inspection procedure. The results can be utilised in application and evaluation of quantitative RI-ISI analyses. The results of the POD analyses may justify the use of rather simple POD curve assumptions in RI-ISI. Such simplified POD curves would be much easier to derive and justify e.g. from the inspection qualification process than more complex functions. The study can also help to clarify what level of POD needs to be proven at qualification of an inspection procedure. In some cases the results might justify relaxation of the required inspection capability and qualification.

Secondly, the project benchmarks tools used in Nordic countries for structural reliability calculations, with focus on effect of inspections on the leakage probability estimates. Such benchmarking can provide added confidence on the modelling approaches, or identify further development needs.

1.3 Scope of the study

The study includes probabilistic analyses performed with different methods, conducted by three different organisations: VTT (Technical research centre of Finland), Inspecta (Sweden) and JRC (Joint Research Centre, The Netherlands). Each of the methods was used to assess failure probabilities for three different NPP welds using different POD-curves. The scope of the study was to:

- evaluate the capability of the different methods for assessing failure probabilities of the welds when subject to inspections modelled with different POD-curves;
- benchmark the results obtained with the different methods;
- assess the importance and effect of POD-curve assumption on the results, across all methods;
- perform sensitivity analyses for some important factors, such as the distribution of the initial cracks and the inspection intervals.

2 BACKGROUND AND EARLIER STUDIES

This NKS study has connection to several earlier research and development projects on both structural reliability modelling and NDT considerations. In this section we shortly summarise the most relevant studies with involvement of the participating organisations. These studies are:

- EC Shared Cost Action NURBIM 2001-2004 (Inspecta, JRC, VTT)
- ProLBB 2006-2007 (Inspecta)
- Relationship between RI-ISI and inspection qualification 2006-2008 (JRC, VTT)
- Studies on inspection strategies 2006 (Inspecta)

2.1 NURBIM project

NURBIM, Nuclear Risk-Based Inspection Methodology, was an EC funded shared cost action within the 5th framework programme (11/2001 - 6/2004). The objective of the NURBIM project was to develop improved procedures to identify where the highest likelihood of damage/failure is located in passive systems, structures and components, and provide quantitative measures of the associated risk.

The following issues were addressed in NURBIM [1]:

- Review of relevant operating experience concerning PWR's and BWR's to compile a database of degradation mechanisms
- Establish guidelines for general criteria to be met by structural reliability models (SRMs)
- Suitability of SRMs for different damage mechanisms and integration of qualitative and quantitative analyses
- Review and recommendations for SRMs and associated software (based on SCC and fatigue benchmark study)
- Establish the interface between probability of failure and consequence for use in an RI-ISI programme
- Criteria for identifying risk significant locations and worked example of cost-benefit analysis
- Investigation of the relationship between RI-ISI and inspection qualification
- Case study on primary piping systems of a BWR

Two work packages of NURBIM are of special interest regarding the PODRIS project: WP4 on review and benchmarking of structural reliability models (SRMs) and related software, and WP7 on the relationship between RI-ISI and inspection qualification.

In the benchmarking exercise (WP4), two cases were analysed: one considering SCC as degradation mechanism, and one on thermal fatigue. Altogether six SRM codes were used to calculate failure probabilities for various pipe sizes under different loading conditions and a large number of parameter variations. Based on the evaluation of the results, a set of requirements and recommendations for the use of SRMs and associated software in risk based inspection studies were formulated.

This working package WP7 investigated the influence of the defect detection reliability on the failure probability of components. The work focused on how the ENIQ inspection qualification could lead to quantifiable assessment of detection probability and be used in structural reliability models. The work included some numerical investigations to assess the sensitivity of calculated risk reduction to the level of detail within the POD curve.

2.2 Probabilistic LBB-study – ProLBB

2.2.1 Background

The view on pipe fracture and how one can prevent it and also how one should protect against the consequences of pipe fracture has varied during the years. In the beginning pipe fracture of large pipes was a purely hypothetic event, defined to calculate the loss of coolant that must be replaced with the emergency cooling systems. Fractures on these pipes became a design limiting event in the design of the containment and the emergency cooling systems. However, the possibility was noticed that a sudden pipe fracture actually could occur which meant that requirements on limiting the consequence of this event were needed. The main concern was pipe whips, and therefore a large number of pipe whip restraints were installed (to withstand these types of guillotine breaks).

Later, certain disadvantages with pipe whip restraints were noticed. These where mainly related to an increased risk for lockups of the piping system in certain load situations, but also difficulties to perform the non-destructive testing (hard or impossible to test certain welds etc.) and an increased dosage rate for the people performing the inspection. Due to the above reasons, new analyses and pipe fracture experiments were performed. These indicated that the probability for a sudden pipe fracture on a large pipe, without any damage mechanism, was very small. These type of analyses, introduced the so-called LBB (Leak Before Break) concept that was formalised in the American design criteria GDC-4 in 10CFR50 and also the introduction of one deterministic LBB procedure in SRP 3.6.3. With Leak Before Break, it is meant that the piping system has a design, operational conditions etc. that the probability of failure is sufficiently small and that measures have been taken so that damage (if it occurs) with a large probability leads to a detectable leak with a sufficient margin before rupture.

Also the regulatory view on LBB has varied internationally during this time. In USA and many European countries, LBB is now accepted to be used as one way to account for local dynamic effects following a pipe rupture. In Sweden SSM has issued new regulations, SSMFS 2008:17 [2], where one allows for the use of LBB as a way to demonstrate a sufficient protection against the consequences of a guillotine break and not having to install pipe whip restraints.

With the new regulations on LBB there was a need to develop guidelines on how to demonstrate the existence of Leak Before Break. As a complement to these guidelines and also to help identify the key parameters that influence the resulting leakage and failure probabilities, a probabilistic LBB approach was developed.

2.2.2 ProLBB – a probabilistic LBB approach

The probabilistic LBB approach [3] was implemented using the calculation engine from the software ProSACC [4]. The reason for not using the original version of the ProSACC program was that a more general application was needed that could have an arbitrary parameter as a random variable and also that new distribution functions were needed to implement the probabilistic LBB approach. Finally a new stress intensity factor solution for off-centre cracks was included in the calculation engine.

Two different probabilities were calculated using this implementation of the probabilistic LBB approach (ProLBB approach):

- Probability of leakage (given the existence of a surface crack).
- Probability of fracture (given the existence of a leaking through-thickness crack).

The influence from the quality of the NDT procedure (by using the information from different POD curves) is not taken into account when calculating the different probabilities. Also, the influence from the leakage detection system is not included in the current implementation. However, the information regarding detection of cracks and leakage could be included in an expanded probabilistic LBB approach.

The results for the baseline cases were generated using FORM to get the most probable point of failure and then using Monte Carlo Simulation with Importance Sampling to get a better estimate of the very small probabilities generated in most cases.

The major part of the sensitivity study consists of checking how the probability of fracture changes when varying a number of parameters one by one, keeping all other parameters fixed at their baseline values (the baseline cases correspond to the "best estimate" values of all parameters, reflecting actual plant conditions for each case). However, a more formal sensitivity analysis was also presented. This analysis tries to answer the following questions:

1) What parameter contributes the most to the calculated fracture probability?
2) What parameter change has the most influence on the calculated fracture probability?

This formal sensitivity analysis is generated using information from an expanded FORM analysis.

In the probabilistic approach, the following parameters are considered as being deterministic:

- Pipe diameter;
- Pipe wall thickness;
- Internal pressure;
- Temperature;
- Leakage flow rate;
- Crack morphology variables.

In the probabilistic approach, the following parameters are considered as being random:

- Crack length (both for surface cracks and through-thickness cracks)
- Crack depth (surface cracks only);
- Off-centred position of crack;
- Fracture toughness;
- Yield strength;
- Ultimate tensile strength;
- Primary membrane stress;
- Primary global bending stress;
- Secondary global bending stress (expansion stress).

The interface to the calculation engine is written so that more parameters could easily be considered as being random (if needed). It is also possible to consider that some (or all) of the random parameters are treated as being correlated with one another.

2.2.3 Conclusions from the ProLBB study

The main conclusions, from the ProLBB study, are summarized below.

- The probabilistic approach developed in this study was applied to different piping systems in both Boiling Water Reactor (BWR) and Pressurised Water Reactor (PWR) units. Pipe sizes were selected so that small, medium and large pipes were included in the analysis. Three BWR and three PWR pipes were selected to be the baseline cases. The present study shows that the conditional probability of fracture is in general small for the larger diameter pipes when evaluated as function of leak flow rate. However, when evaluated as function of fraction of crack length around the circumference, then the larger diameter pipes will belong to the ones with the highest conditional fracture probabilities.
- The total failure probability, corresponding to the product between the leak probability and the conditional fracture probability, will be very small for all pipe geometries when evaluated as function of fraction of crack length around the circumference. This is mainly due to a small leak probability which is consistent with expectations since no active damage mechanism has been assumed. This also means that it can be very conservative to assume the existence of a leaking crack when there is a high confidence of the absence of any active damage mechanism.
- The influence from an off-center crack position on the conditional probability of fracture is not important when assuming a uniform distribution around the circumference of the crack position. This is because the result is dominated totally by the center crack position. However, if the crack position is treated as a deterministic parameter, the conditional probability of fracture is strongly dependent on the position of the crack, especially for large off-center cracks.
- The weld residual stresses have quite an impact on the resulting fracture probabilities, especially for smaller cracks (this is relevant both for small and large pipes).
    - The difference (with/without the weld residual stresses) would be smaller if only taking the weld residual stresses into account in the calculation of fracture probability and not in the calculation of leakage flow rate (which is incorrect, since both effects should be included in the analysis).
    - The influence from the weld residual stresses on the calculation of leakage flow rate is largest for a thin-walled pipe. This is reasonable, since a local bending stress is used which closes the crack.
    - The influence from the weld residual stresses on the calculation of fracture probability is largest for one of the thick-walled pipes. This is related to the calculations and the fact that this case is more sensitive to the chosen fracture toughness in the calculation of probability of fracture.
- The conditional fracture probabilities are relatively sensitive to the crack morphology. The conditional fracture probability as function of leak flow rate will be higher for stress corrosion cracks as compared to fatigue cracks. This is because a stress corrosion crack has a crack morphology which restrains the leak flow rate more as compared to a fatigue crack which means that you need a larger crack to obtain an equivalent leak flow rate.
- In the formal sensitivity analyses, it is shown that the standard deviation of the yield strength has the strongest influence on the conditional fracture probability (when comparing with the mean values and standard deviation values of all the parameters included in the analysis). This is reasonable, since the analysis is mainly controlled by the limit load for all crack lengths up to very long cracks.
- The study has given an indication of the relation between the deterministic LBB-criteria (ratio of critical crack length and leakage crack length equal to 2 and margin of 10 on a detectable leak flow rate) and the corresponding conditional fracture probability. As expected, it is easier to fulfil the deterministic LBB-margins for a large diameter pipe compared to a small diameter pipe.

2.3 Project on the relationship between RI-ISI and inspection qualification

A project on the relationship between RI-ISI and inspection qualification was initiated by the ENIQ TGR, and conducted in 2006-2008. The main objectives of the project were to investigate approaches to quantifying the confidence associated with inspection qualification, and to produce guidelines on how to relate inspection qualification results, risk reduction and inspection interval.

Three approaches to quantify the ENIQ qualification process were considered and applied in pilot studies. These approaches were 1) a direct judgement method; 2) a Bayesian approach that included weighting and scoring the various parts of the evidence presented in the technical justification; and 3) an approach based on the relationship between POD and margin of detection.

The pilot studies resulted in a set of recommendations related to the quantification of inspection qualification. Particular attention was paid to the development of guidance to support the application of the Bayesian model that combines and quantifies the "soft" evidence from a technical justification with the "hard" evidence obtained from practical trials.

Besides the application of the quantification approaches, the project also illustrated how, if defect growth can be modelled, it is possible to link inspection qualification results, risk reduction and inspection interval. In this connection studies on the sensitivity of risk reduction to POD curves level and detail were performed at JRC. In these studies, a simplified approach was used to investigate the effect of POD on the failure probability, given various assumptions concerning the flaw size distribution and the failure probability as a function of the flaw size. The work is reported in the document EUR 21902 EN [12]. Further, some examples of time-dependent analyses were carried out and documented in the final report to illustrate additionally the effect of inspection interval and crack growth rate on the failure probability. The full report [13] can be downloaded from the ENIQ website (http://safelife.jrc.ec.europa.eu/eniq)

2.4 Other Swedish studies - different inspection strategies

A study [14] aimed at determining the risk reduction for different inspection strategies for welds connecting to valves in systems 321, 323 and 327 in Forsmark Unit 3. These welds have to be inspected recurrently according to the regulation SKIFS 1994:1 [15] due to the possibility for Intergranular Stress Corrosion Cracking (IGSCC). Inspection using Ultrasonic Testing (UT) is a generally accepted technique for detection of this type of cracks, and is considered as a reference inspection method. However, these welds are difficult to inspect by UT due to the geometry and damping in the weld material. A possible alternative is to use Penetrant Testing (PT).

The risk of core damage with respect to failure of the welds at valves in systems 321, 323 and 327 in Forsmark unit 3 was analysed by applying the probabilistic NURBIT model. The main conclusions were:

- Inspection with penetrant testing (PT) from the inside results in the same risk reduction as the reference inspection with qualified ultrasonic (UT-01).
- The risk level of welds at the valves is much lower than the risk level of welds between pipes in these systems, even after planed inspections.

- It is shown that several welds have a low or very low risk, and that inspection of these welds has negligible effect on reducing the risk. Inspections of these welds can be excluded.
- An optimized inspection programme for PT is developed, which focuses inspection to high risk locations where inspection will have significant effect.
- The risk reduction from the proposed programme is almost identical to that of the reference inspection programme based on qualified ultrasonic (UT-01). In addition, the irradiation dose is significantly lower.
- The sensitivity of the risk ranking of the welds is investigated with respect to reasonable changes of the following parameters; the POD-curves for PT, the IGSCC induced crack growth rate, weld residual stresses and the fracture toughness. The welds of the three valves are included based on the results of the sensitivity analyses.
- Selection of inspection sites for confirmation of inactive damage mechanisms and search for unexpected damage is included in the recommended programme.
- It is shown that a risk reduction of about 10 is obtained solely by the leakage detection system. The risk reduction achieved by future inspections is about 3, when considering the inspections that already have been performed. This shows that the leakage detection system is an important measure to reduce the risk.

3 STRUCTURAL RELIABILITY ANALYSIS APPROACHES

In this section we summarise the main features of the structural reliability analysis tools and approaches applied in the project. Four approaches were used to analyse the same cases in order to identify differences in the obtained results. Inspecta used the NURBIT code and the PRoSACC tool, VTT run the analyses with VTTBESIT code, and JRC used a Monte Carlo simulation program run with the Matlab analysis software.

3.1 NURBIT

NURBIT [9, 10] is a procedure and software for risk informed planning of inspection. The model considers the degradation mechanisms stress corrosion cracking (SCC) and high cycle fatigue. The leak probability and the fracture probability are estimated for each specific weld in a piping system. The model allows quantitative evaluation of the influence of different inspection intervals and inspection capability upon the failure probability of each weld. The failure probability is strongly dependent on the actual loading conditions at each weld. For risk evaluations the probabilities are combined with the consequence which is measured by the conditional core damage probability (CCDP) for each weld, obtained from PSA results.

The deterministic model

NURBIT is based on very detailed and complete deterministic fracture mechanical models describing crack growth, for estimation of the crack opening areas and leak rate for through wall cracks, and for evaluation of the event of fracture or plastic collapse [11, 12]. In general, failure of piping due to crack growth is, at normal operation conditions and in materials commonly used, first revealed by the event of wall penetration and leakage, and not by total fracture of the pipe. However, when load events in addition to the normal operation loading are considered, fracture is likely to occur even before wall penetration. Thus, in NURBIT several load cases are defined and evaluated. Further, for the leakage to result in a forewarning event, the leak rate from the penetrating crack has to be large enough to be detectable by the plant leak monitoring systems (well in advance before the crack reaches critical size for fracture). The probability of a large leak or rupture to occur is affected by the detection probability of a small leak, before it develops to a larger leak. Leak detection thus is related both to the probability and the consequence of failure. The NURBIT model evaluates all these possible events at growth of circumferential cracks due to stress corrosion cracking and high cycle fatigue in piping components.

When a surface crack is initiated, its growth is modelled by fracture mechanical models taking into account effects of the complex crack shape that generally evolve during the wall penetration event [12]. When the crack depth reaches 90% of the wall thickness the crack is recharacterized to a through wall crack, normally having a shorter length at the outside than at inside of the wall], se Fig 1. It has been highlighted that the leak rate is very dependent on the crack shape and the crack opening profile that develop for through wall cracks, and these are in turn is very dependent on the residuals tress distribution (and crack growth relation).

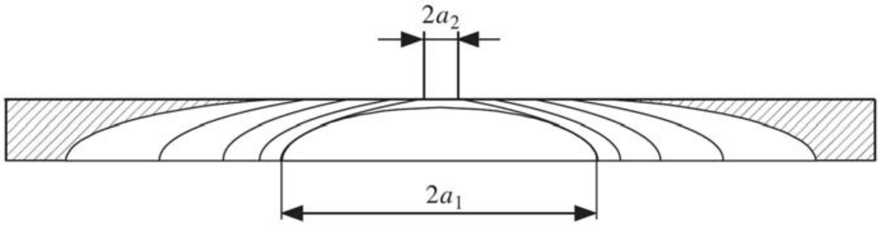


Figure 1 **The evolution of the crack shape at wall penetration of a SCC / fatigue crack. In this example the loading is predominantly through-wall bending.**

The mean leak flow rate for the through-wall crack is calculated using a model for two-phase flow. The event of final fracture or plastic collapse is for all crack sizes evaluated using the R6-procedure. Consideration of plasticity effects is also important at calculation of the crack opening area, for accurate leak rate estimation.

The deterministic fracture mechanical procedure for calculation and evaluation of the growth, leakage and fracture of cracks was developed in [11], resulting in the code LBBPIPE. In the procedure crack growth is calculated to the time for penetration of the outer surface and further to the time of rupture. In addition the leak rate just before rupture is calculated. Wit rupture of the pipe is here meant that either fracture, $J > J_c$, or that the pipe suffers plastic collapse if the limit load is exceeded. The crack driving force J is here calculated by the R6-procedure and J_c is the corresponding fracture toughness.

The probabilistic model
With the above deterministic model as a basis, a probabilistic model was developed for NURBIT in order to estimate for individual welds the probability for small and large leak rates, and the probability for failure [13-15].

The intention when developing the probabilistic approach was to capture the main random behaviour and uncertainties, based as much as possible on data that is obtained from service records and damage statistics for nuclear power stations. The model parameters simulated as random were confined to only a few chosen variables. Another objective was to keep the probabilistic evaluation of the model simplified in order to achieve short calculation times. Thus, the probabilistic evaluation of the model is simplified by assuming that the randomness is captured by taking into account only; (i) a crack initiation rate, (ii) randomness in initial crack length, (iii) the crack detection reliability, and (iv) the leak detection reliability. All other parameters in the model are assumed to be deterministic.

Below the random variables in the model are discussed in some more detail.

(i) The crack initiation rate is assumed to be constant and is estimated based on damage statistics, see e.g. [5]. Initiation is defined to mean that a crack of observable depth (about 1 mm) has developed, and it is assumed to be independent of the loading.

(ii) The randomness in the initial length of inside surface cracks is described using a distribution function, truncated at full circumferential cracks. Generally an exponential distribution is assumed. The distribution is assumed to be independent of the loading. The distribution is intended to be developed by using damage statistics, see e.g. [5]. The observed cracks are calculated backwards to an initial depth of 1 mm using mean growth data, and a length distribution is fitted. The randomness/uncertainty in the crack development in the model is fully described via the distribution for the initial crack length. The process for stress corrosion crack growth is not well known (uncertainties in influencing parameters), and thus the initial crack length distribution may also suffice as reflecting the randomness in the growth rate.

(iii) The effect of in-service inspection is taken into account using an inspection reliability model. The user defines an inspection interval, and the inspection reliability is described by a probability of detection function, POD, which for ultrasonic testing is a function of crack depth. When an inspection is performed the probability of not detecting the crack is 1 - POD, for the crack depth grown during that time period, and this gives the contribution to the failure probability. In general the conservative assumption is made that only the effect of the last inspection is considered.

(iv) The leak rate is assumed to be normally distributed when evaluating the probability of the estimated leak rate being lower than the specified detection limit.

Due to the assumptions made, the probabilities can be calculated from a sum of numerical integrations with respect to the initial crack length only [14]. The integration results in an average yearly failure probability for the remaining operating time. The calculation is very fast compared to the numerical methods needed for a model including more random variables.

The estimates from the NURBIT model having very few random variables can be expected to differ from the results from a model that treats more parameters as random variables.
However, the code has been validated to other structural reliability models in the NURBIM project [9] and it was concluded that the model reflect well the importance of different influencing variables.

As outlined above the main description of the randomness/uncertainty in NURBIT is via the exponential distribution for the initial crack length. In cases when other variables become the true controlling variable, the resulting estimates can be poor. For example, in cases of very low normal operation loading and very low crack growth rates, it may occur that not even a full circumferential crack is predicted to grow trough the wall for the considered operating time, and the model will predict the failure probability to be identical to zero. This case illustrates the limitation of the model to describe exceptional situations, and the choice to describe the scatter in the crack growth process solely via the initial length distribution (related to damage statistics) can result in rough results. However, elimination of this limitation by introducing probabilistic treatment of more parameters has to be balanced against the advantages of a model with detailed evaluation of all the events before failure having a short calculation time.

For risk evaluations the calculated probabilities are combined with the consequences. The conditional core damage probability is determined for the different weld positions in Level 1 PSA-analyses. Generally, the CCDP for Loss-Of-Coolant Accident (LOCA) is the assumed consequence given a large leakage or total pipe break. The consequence for a small leak is assumed to be the CCDP for a normal shutdown of the plant.

NURBIT includes a module for the selection of safety significant sites to inspect based on evaluation of the plant-specific relative risk levels. The effect of the inspection interval is systematically included in the quantitative optimisation process. The software package also provides means to optimise the inspection programme with respect to costs and radiation dose for the inspection personnel.

Studies have shown that neglecting the effect of leak detection in the assessment of probability of failure may cause an unjustified focus on low-risk components for inspection selection. When applying the model in general the leak detection reliability is systematically taken into account. In this benchmarking study the failure event is defined as leakage solely, and it will be assumed that very small leak rates are detectable, for the reason of comparisons to the other models.

3.2 ProSACC

ProSACC is a computer code [4] that evaluates leak and break probabilities for SCC or fatigue induced circumferential or axial cracks in piping components or cracks in plates. ProSACC consists of a deterministic and a probabilistic part.

3.2.1 The deterministic part of ProSACC

The deterministic part of the software ProSACC may be used both for assessment of detected cracks or crack like defects and for defect tolerance analysis. The procedure, which is based on the R6-method [16], could be used to calculate possible crack growth due to fatigue or stress corrosion and to calculate the reserve margin for failure due to fracture (if wanted, including a limited amount of stable crack growth) and plastic collapse. ProSACC also has an option, which enables assessment of cracks according to the 1995 edition of the ASME Boiler and Pressure Vessel Code, Section XI. Appendices A, C and H for assessment of cracks in ferritic pressure vessels, austenitic piping and ferritic piping, respectively.

Within ProSACC the following components and crack types may be analysed (both in the deterministic and probabilistic part of the software):

- Plate with a finite surface crack;
- Plate with an infinite surface crack;
- Plate with an embedded crack;
- Plate with a through-thickness crack;
- Cylinder with a finite axial internal surface crack;
- Cylinder with an infinite axial internal surface crack;
- Cylinder with a finite axial external surface crack;
- Cylinder with an infinite axial external surface crack;
- Cylinder with an axial through-wall crack;
- Cylinder with a part circumferential internal surface crack;
- Cylinder with a complete circumferential internal surface crack;
- Cylinder with a part circumferential external surface crack;
- Cylinder with a complete circumferential external surface crack;
- Cylinder with a circumferential through-wall crack;
- Sphere with a through-wall crack;
- Bar with a finite surface crack.

3.2.2 The probabilistic part of ProSACC

The probabilistic part of the software ProSACC is based on a probabilistic procedure that calculates two different failure probabilities, P_F:

- Probability of failure, defect size given by NDT;
- Probability of failure, defect not detected by NDT.

The procedure uses two different limit state functions based on a simplified R6 failure assessment curve.

Within the procedure, the following parameters are treated as random parameters:

- Fracture toughness;
- Yield strength;
- Ultimate tensile strength;
- Primary stresses;
- Secondary stresses;
- Defect size (depth) given by NDT;
- Defect distribution (when a defect is not detected by NDT);
- POD-curve (when a defect is not detected by NDT);
- Constants in the fatigue crack growth law;
- Constants in the SCC crack growth law.

As mentioned above, the failure probability integral is very hard to solve using numerical integration. Instead, the following numerical algorithms are included within the procedure:

- Simple Monte Carlo Simulation (MCS);
- First-Order Reliability Method (FORM).

MCS is a simple method that uses the fact that the failure probability integral can be interpreted as a mean value in a stochastic experiment. An estimate is therefore given by averaging a suitably large number of independent outcomes (simulations) of this experiment.

An advantage with MCS is that it is robust and easy to implement into a computer program, and for a sample size $N \rightarrow \infty$, the estimated probability converges to the exact result. Another advantage is that MCS works with any distribution of the random variables and there is no restriction on the limit state functions. However, MCS is rather inefficient, when calculating failure probabilities, since most of the contribution to P_F is in a limited part of the integration interval.

FORM uses a combination of both analytical and approximate methods, when estimating the probability of failure. FORM is, as regards CPU-time, extremely efficient as compared to MCS. Using the implementation within ProSACC, quite accurate results for failure probabilities between 10^{-1} and 10^{-15} can be achieved. A disadvantage is that the random parameters must be continuous, and every limit state function must also be continuous.

Details on the calculation methods can be found in ProSACC handbook [4].

No formal sensitivity analysis is done within the procedure. However, simple sensitivity factors are calculated when using FORM. These sensitivity factors use the most probable point of failure (MPP) in a standard normal space. Using ProSACC, it is possible to estimate partial safety factors, given a target failure probability and characteristic values for the random parameters included in the analysis.

3.3 VTT approach

The VTT approach combines the use of a probabilistic fracture mechanics (PFM) calculation tool VTTBESIT and a separate Matlab based Markov model module for modelling inspection strategies [17]. In the first phase the PFM simulations are carried out. The purpose of the simulations is to gain probabilistic insight concerning crack growth in the piping component walls.

In the second phase, the analyses are based on Markov processes. The states of the Markov process correspond to crack penetration depths in the material, and the transition probabilities from a lower state to higher states (deeper cracks) are generated from the results of the PFM simulations. The effects of inspections are included in the model as transitions from a cracked state to a flawless state.

3.3.1 Probabilistic Fracture Mechanics

VTTBESIT code has been developed by the Fraunhofer-Institut für Werkstoffmechanik, Germany, and by VTT. With the VTTBESIT it is possible to quickly compute mode I stress intensity factor values along the crack front as well as crack growth. The code was originally intended for deterministic fracture mechanics based crack growth analyses, but it has been modified by adding probabilistic capabilities to the code.

The probabilistically treated crack growth analysis input data parameters are listed below:

- depth of initial cracks;
- length of initial cracks;
- frequency of load occurrence.

Other crack growth analysis input data parameters are considered to have deterministic values.

In the VTTBESIT analyses, the amount of crack growth in each time step is calculated from the respective crack growth (for instance fatigue or stress corrosion cracking) equation. The simulation ends either when the crack depth reaches the outer pipe surface, or the time cycles reach the end of plant lifetime. For each analysed case, from hundreds to thousands separate simulations are calculated, and for each of these, values of the above mentioned distributed input data parameters/variables are sampled at random from the respective probabilistic distributions. Each run is a 60-year simulation with the crack depth calculated at 1-year intervals, conditional on the existence of an initial flaw. The annual crack depth information for each simulation is transferred to the second phase of the analyses.

3.3.2 Markov Model for Crack Growth

In the second phase, the analyses are based on Markov processes. Markov process is a stochastic process in which the probability distribution of the current state is conditionally independent of the path of past states, a characteristic called the Markov property. In our application the states of the Markov process correspond to crack penetration depths in the component walls, and the transition probabilities from a lower state to higher states (deeper cracks). On the other hand, the effects of inspections are included in the model as transitions from cracked state to a flawless state. A similar approach to study inspection strategies using Markov models has been suggested by Fleming [19], the main novelty here is the use of PFM modelling to generate transition probabilities to model the crack growth.

The principle of a simple Markov model is illustrated in Fig. 2.

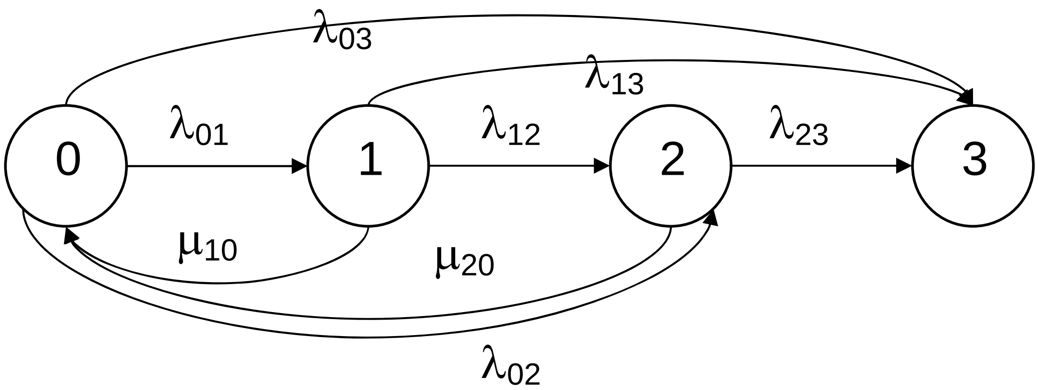


Figure 2 **Illustration of a Markov model for degradation and repair.**

In this illustration we have defined the following states: 0 = no detectable flaw, 1 = a detectable flaw, 2 = detectable leak, 3 = rupture. λ_{ij} and μ_{ij} are transition rates (or probabilities per cycle) from state i to state j. λ_{ij} symbolise growh rates, while μ_{ij} are describing the repair rates.

The state transition matrix for the above system is:

$$M = \begin{pmatrix} 1-\lambda_{01}-\lambda_{02}-\lambda_{03} & \lambda_{01} & \lambda_{02} & \lambda_{03} \\ \mu_{10} & 1-\mu_{10}-\lambda_{12}-\lambda_{13} & \lambda_{12} & \lambda_{13} \\ \mu_{20} & 0 & 1-\mu_{20}-\lambda_{23} & \lambda_{23} \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (1)$$

In our discretised model, we use probabilities instead of rates. We can also define several states as a function of flaw depth, and define different flaw detection probabilities for each depth state.

Transition probabilities from one state to the other higher states are generated from the results of the PFM simulations. From the simulations we obtain information on the flaw depth once a year, and this size is assigned to a state representing a certain range of depth. The data tells how many years has been spent in each of these states, and if there is a transition to a higher state. The transition probability from state *i* to *j* *(j>i)*, p_{ij}, is obtained by dividing the number of transitions from *i* to *j* by the number of years spent in state *i*. In theory any number of states can be used, but the PFM simulation step limits this number. Depending on the application, a suitable number of states is between 5 and 10.

The general discrete-time Markov process is:

$$\overline{p}_t = \overline{p}_{t-1} \times M \quad (2)$$

where $\overline{p}_t$ (*t* = 1,2,3…) is a vector containing the state probabilities (i.e. probability that the flaw has advanced to that state) for step *t*, and *M* is a matrix containing the state transition probabilities. $\overline{p}_0$ is a vector describing the initial flaw depth distribution of the component.

For better modularity and ease of application this basic Markov process is modified to use two different state transition matrices. The degradation matrix M_{deg} models the crack growth, and inspection matrix M_{ins} models the inspections. While the degradation matrix affects the state probabilities each year, inspections affect it only on those years inspections are performed, yielding the following modified discrete-time Markov process:

$$\overline{p}_t = \overline{p}_{t-1} \times M_{\deg} \times \left(B(t) \cdot M_{ins} + (1 - B(t)) \cdot \mathrm{I} \right) \tag{3}$$

where *B(t)* is a Boolean function with value 1 if inspections are performed at time step *t* and 0 if no inspections are performed at time step *t*, and I is a unit matrix. While any length can be chosen for the time step, one year seems natural for RI-ISI application, since the outages during which inspections could be performed are usually carried out once a year.

The Markov process was coded and the results were calculated with Matlab software.

3.4 JRC approach

The JRC approach was based on a probabilistic implementation of the R6 code [16], developed in the UK by British Energy and used a discrete time Markov process analysis to model the extent of crack grow at each inspection. The approach was coded using the software MATLAB.

The probabilistically treated input data were:

- defect depth;
- defect length;
- yield stress;
- ultimate tensile stress;
- fracture toughness.

The Markov process is a stochastic process in which the probability distribution of the current state is conditionally independent of the path of past states, but only depends on the last state. In this approach, the states of the Markov process correspond to different crack depths, and the transition probabilities correspond to jumps from a given state to a higher one, where the crack is deeper. The effects of an inspection are modelled as transitions from a cracked state to a flawless one.

Two MATLAB modules were developed. The first module (TRANS_MATRIX) obtained the Markov transition probabilities, and the second (MARKOV_CHAIN) calculated the failure probabilities by implementing the Markov process.

Transition probabilities were generated from the results of the probabilistic fracture mechanics simulations. The code in the module TRANS_MATRIX was designed to be as flexible as possible, allowing for instance the user to select the number of transition states. These included a partition of the component's wall thickness into n equal intervals, plus one state for "flawless component" and one state for "failed component".

Failure was defined as a crack reaching 80% of the wall thickness. This assumption is clearly very conservative, but the stress intensity factor solutions that were implemented in the R6 approach were valid only up to this point, and therefore it was not possible to consider more sophisticated states such as a leaking crack.

The main element of the module TRANS_MATRIX consisted in a MONTECARLO cycle, repeated a very high number of times, for each crack intervals previously defined. The number of runs, N, to obtain a single row (or column) of the transition matrix for one of the cases investigated was typically 100,000, as it was found that increasing it considerably increased the analysis time with only little increase in the accuracy of the calculation. Thus, for each crack state (interval), a random instance was obtained N times, by sampling from the appropriate distributions. In each instance, a new crack depth (and therefore a new state) was reached (including failure if the crack was calculated to exceed 80% wall thickness) and the transition matrix was populated.

The second module, MARKOV_CHAIN, calculated the evolution of yearly failure probabilities with time, taking into account the progressive degradation (modelled by the transition matrix obtained from the previous module) and the inspection activity (modelled by a second state transition matrix).

4 ANALYSED CASES

Three piping weld cases were selected for the study. Two of them were from a BWR unit and one from a PWR unit. In all cases stress corrosion cracking (SCC) was assumed to be the degradation mechanism. The calculations were performed for a 60 year lifetime.

Case 1: a piping weld in a BWR system 313, with wall thickness of 8 mm (**BWR1**)

Case 2: a piping weld in a BWR system 321, with wall thickness of 25 mm (**BWR2**)

Case 3: a weld in a PWR primary loop, with wall thickness of 64.85 mm (**PWR3**)

The following input parameters that are needed for the probabilistic fracture mechanics calculations were settled for the cases:

- Pipe and defect geometries; pipe dimensions, defect depth and length distributions;
- Loadings; internal pressure and temperature, primary and secondary global bending loads, welding residual stresses;
- Material data; yield stess, ultimate tensile stress, fracture toughness, crack growth law parameters, Young's modulus, Poisson's ratio.

For the case 1 (BWR1) and 3 (PWR3), the geometry as well as the loading and material data were taken from the ProLBB study [3]. For the case 2 (BWR2), realistic input data was obtained from data for a weld in a Finnish power station.

A detailed compilation of the used input data is presented in Appendix 1. A few comments can be given on the input data of the selected cases. The cases were selected to cover a range of pipe thicknesses, but arbitrary with respect to the other parameters. The membrane and bending stresses obtained for these cases are rather moderate, with an exception for the membrane stress part in case PWR3. Note that only normal operation load is considered and no loads from regular upset events. For simplicity, the weld residual stress distribution is assumed to be a linear distribution through the thickness of the pipe in all three cases, which is a rough approximation for the case PWR3. Further, the obtained weld residual stress is very low in cases BWR2 and PWR3. In total the applied stresses are rather low, and it can be expected that this contributes to low leakage probabilities for these cases.

4.1 POD assumptions

The inspection reliability is described using probability of detection (POD) functions. As reference cases the following inspection assumptions were used:

1. No inspections
2. Inspections at 6 year interval, with POD according to the Eqn. 19 in [18]:

$$POD(a) = \Phi[0.1218+0.372 \cdot \ln(a)]$$

Where Φ denotes the normalised Gaussian distribution, and a is the crack depth.

In order to study how much the use of a simplified POD influences the results, two simplified POD functions were defined for the analyses. These simplified PODs were conservative step functions with respect to the base case POD-curve. These PODs were formulated by taking one point (a_{ref}, pod_{ref}) from the reference case POD-curve, and assuming for $a < a_{ref}$ POD = 0, and for $a \geq a_{ref}$ POD = pod_{ref} .

Two different simplified step POD functions were assumed as follows:

1) A detection limit of 2 mm, i.e. flaws below 2 mm are not detected, were used as a_{ref}. The probability of detection for flaws above 2 mm is constant, pod_{ref}, corresponding to the POD for a 2 mm flaw according to the equation above (pod_{ref} =0,65).
2) As an upper assumption a detection limit of 80% of the wall thickness were used as a_{ref}. The probability of detection for flaws above 80% of the wall thickness is constant, corresponding to the POD determined by the equation above at 80% of the wall thickness in each case.

The background for the assumed step functions is as follows: a typical detection limit for ultrasonic testing systems is 2 mm. The value of a_{ref} = 80% of the wall thickness were chosen as an extreme case, since this is the maximum allowable crack size. Figure 3 illustrates the two simplified PODs for the Case 3 with wall thickness 64,85 mm.

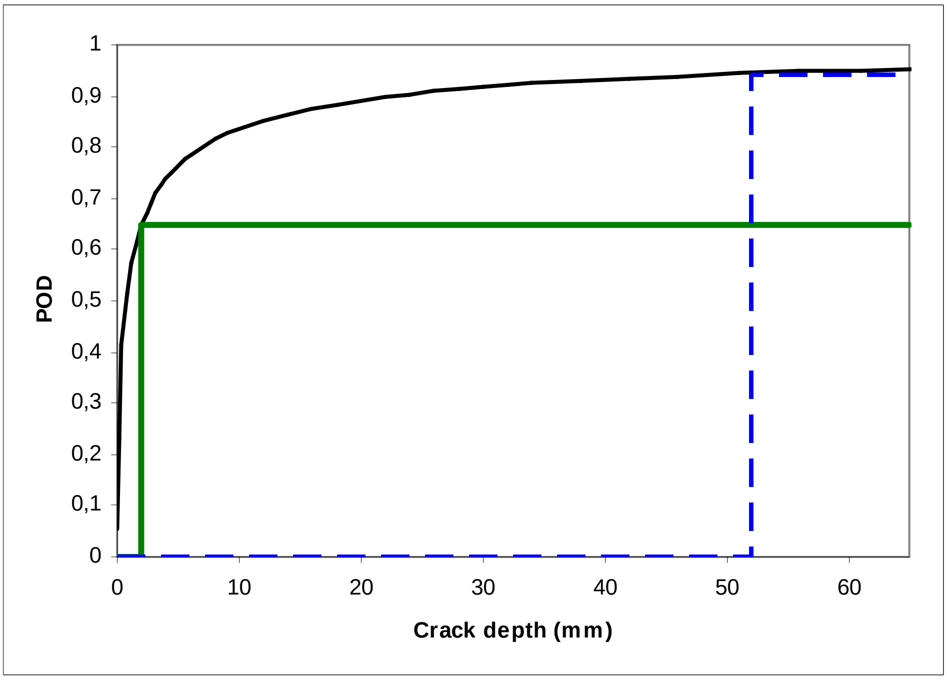


Figure 3 Illustration of the simplified PODs.

As a summary, the following four different POD cases were analyzed, using a 6 years inspection interval in the base case:

- **POD (i);** No inspections
- **POD (ii):** The SKI POD function, $POD(a) = \Phi(0.1218+0.372 \cdot \ln(a))$
- **POD (iii):** A simplified POD function with step at 2 mm crack depth, POD=0,65
- **POD (iv):** A simplified POD function with step at 80% of wall thickness

Table 1 summarises the values of POD at 80 % wall thickness for the three pipe cases.

Table 1 Specification of POD (iv), or the 80% limit step functions

Case	80% of wall thickness	POD
BWR1	6,4 mm	0,79
BWR2	20 mm	0,89
PWR3	52 mm	0,94

4.2 Definition of failure event

It is important to define the failure criterion used in the analyses. The failure event was defined as a through wall crack, i.e. a leakage, and the event of fracture were not evaluated. As also discussed in the results section, the different analysis approaches use different approximations of the event of leakage. Leakage was defined for the VTTBESIT, NURBIT and JRC approach, when the crack depth is 100%, 90 % and 80 %, respectively. As the crack growth is rapid during the final stage, this approximation is not expected to be decisive for differences in the results between the approaches.

The reason for approximating the leakage event by a crack depth less than 100% is that stress intensity factor solutions in general are not available for very deep cracks (because they are hard to predict reliable). This in combination with the fact that the crack growth is relatively rapid during this final penetration stage, imply that neglecting the growth in the final 10-20% of the wall has a limited influence on the predicted time to leakage or probability.

In VTTBESIT calculations were run all the way through the wall, but the stress intensity factor solutions used are accurate only to flaw depths up to 80 % of the wall thickness, and extrapolated values were used for larger depths.

The NURBIT code can also evaluate the event of fracture, and Inspecta made some additional calculations to investigate both the leakage probability and the rupture probability when an upset load is included in the analysis.

4.3 Output of the analyses

In all PFM calculations, the development of the failure probability throughout the lifetime of 60 years is evaluated. For the numerical comparison of results, the average yearly failure probability of the last 6 years (the base case inspection interval) is considered.

The effect of inspection assumptions on the leakage probability is quantified by using two measures. The first measure, the Risk Reduction Factor (RRF) is defined as:

$$\text{RRF} = f_{wo\text{-}i}/f_{w\text{-}i}, \tag{4}$$

where $f_{wo\text{-}i}$ is the failure (leakage) probability without inspections, and $f_{w\text{-}i}$, is the failure probability when inspections are taken into account. RRF can take values from 1 to very large numbers. It describes how many times higher the failure probability is if inspections are not made, compared to the case with inspections. This measure was used e.g. in the NURBIM project [1].

The second measure, R, is defined as:

$$R = 1- f_{w-i}/f_{wo-i}\, x100\ \% \tag{5}$$

R takes values in the interval [0,100]. Values of R close to 100 % mean a significant risk reduction due to the inspection. Indeed, a perfect inspection capable of finding all defects of all sizes will reduce the probability of failure f_{w-i} to zero, and therefore R will be equal to 100 %. On the other hand, values of R close to zero mean a small change in risk, due to poor inspections. This measure was used in the JRC study on the sensitivity of risk reduction to POD level and detail [12].

4.4 Sensitivity analyses

In addition to the base case analyses, sensitivity analyses were performed considering two variables; initial crack depth and inspection interval:

- The expected value of the initial crack depth distribution was: a) reduced to 50% of the base case, and b) increased to 200% of the base case,
- The inspection interval was: a) reduced to 1 year and b) extended to 10 years.

5 ANALYSIS RESULTS

In this section the analysis results for the three piping welds BWR1, BWR2 and PWR3 are presented. In section 5.1 results from the structural reliability approaches described in section 3 are presented, showing results for a detailed POD curve and for simplified assumptions on the inspection reliability. In section 5.2 results are compared for benchmarking of the different structural reliability approaches. The influence of assumptions on initial defect size and the inspection intervals is investigated in section 5.3. In section 5.4 additional important features of a complete probabilistic model are demonstrated, first by the influence of considering both the event of leakage and fracture, and second by analysis of other degradation mechanisms as thermal fatigue in a mixing point.

5.1 Impact of POD simplifications on leak probability estimates

5.1.1 VTTBESIT results

Figures 4 - 6, below, show the yearly failure probabilities calculated with the VTT analysis approach for the three piping cases BWR 1, BWR 2 and PWR 3. The results show the yearly probability of leakage when no inspections are performed and when the three different POD curves described in section 4.1 are used to model the inspections. In Figures 4 - 6 the inspections occur at 6 year intervals, which can be seen from the sawtooth behaviour in the graphs showing yearly failure probabilities.

As the VTT method uses a Markov model for accounting for the inspections, the SKI-POD is modelled by 10 discrete steps. The lower crack depth limit in each Markov state is calculated from the SKI POD to form the discretisized POD.

The analysis starts at year 1, but it takes a few years in each piping case for the process to start generate probabilities above zero. This is due to the nature of the probabilistic fracture mechanics calculation model and the Markov process. The transition probabilities from a low state directly to a high state are usually initially zero, which means that a few iterations of the process must be realized before failure probabilities rise above zero.

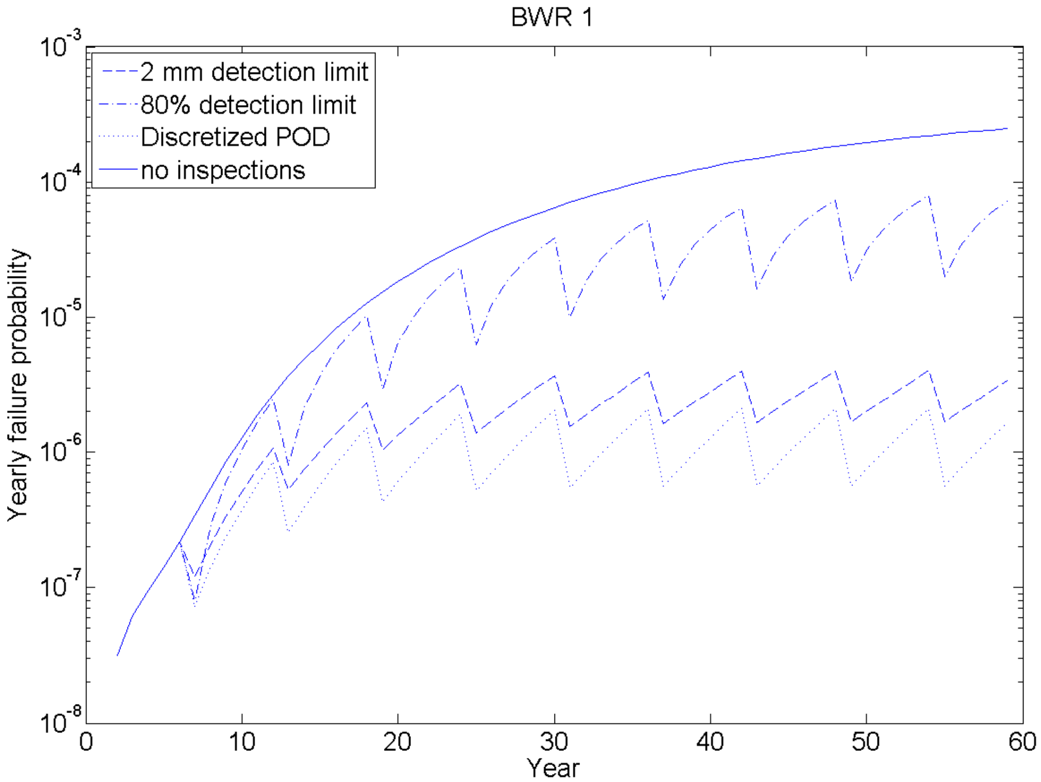


Figure 4 Yearly leakage probabilities for case BWR1 from VTT approach.

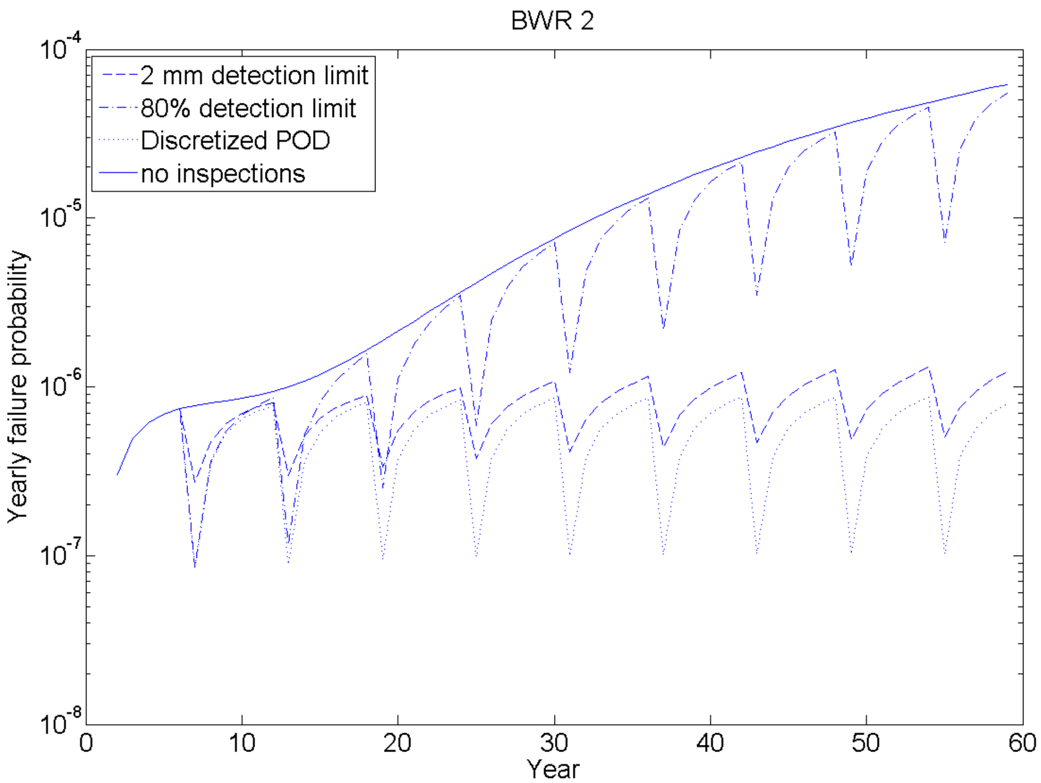


Figure 5 Yearly leakage probabilities for case BWR2 from VTT approach.

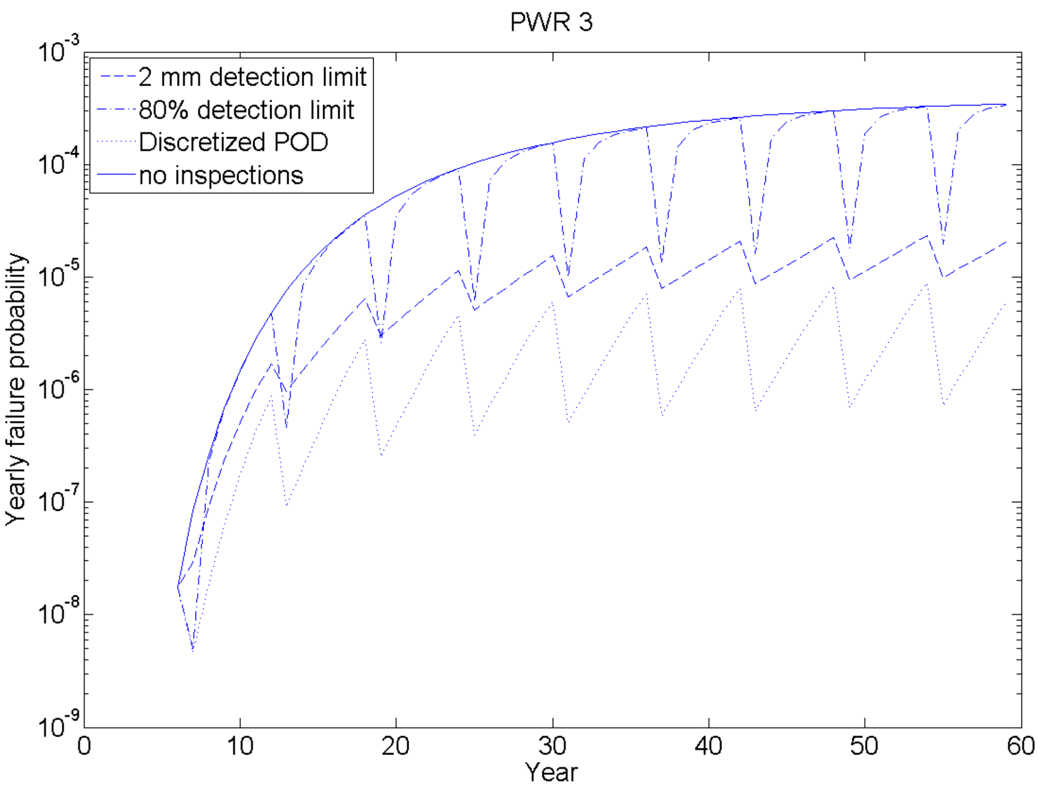


Figure 6 **Yearly leakage probabilities for case PWR3 from VTT approach.**

Table 2 is a summary of the VTT results for the leak probability at 60 years of operation. The probabilities are the average for the last 6 years. Significant risk reduction is shown for all piping cases when the SKI POD or the 2 mm limit simplified POD are used. Using the 80% limit simplified POD curve results in much smaller risk reduction factors, ranging from 1 to 5.

Table 2 **Summary of VTT analysis results**

Case	Inspection	Last 6 years average	RRF	R
BWR1	SKI POD 2 mm detection limit 80% detection limit No inspections	1,22E-06 2,73E-06 5,19E-05 2,34E-04	192 86 5	99 % 99 % 78 %
BWR2	SKI POD 2 mm detection limit 80% detection limit No inspections	5,70E-07 9,71E-07 3,66E-05 5,52E-05	97 57 2	99 % 98 % 34 %
PWR3	SKI POD 2 mm detection limit 80% detection limit No inspections	3,73E-06 1,61E-05 2,47E-04 3,36E-04	90 21 1	99 % 95 % 26 %

5.1.2 Inspecta NURBIT results

Figures 7 - 9, below, show the average leakage probabilities calculated with the NURBIT approach for the three welds. The results show the leakage probability when no inspections are performed, and for the POD curve, and for the two simplified POD models. Inspection is performed by 6 year intervals. By the NURBIT approach an average probability is integrated, and thus the average curves in Figs 7 – 9 are smooth, without any sawtooth appearance.

Also for this approach it takes some years in each piping case before the calculations start to generate probabilities above zero. As discussed in section 3.1 the principal random parameter in NURBIT is the distribution for the initial crack length, and the crack depth and growth rate are treated as deterministic parameters. In a case of only low normal operation loading and very low crack growth rates, it will occur that not even a full circumferential crack is predicted to grow trough the wall for a considered operating time, and the model will then predict the leakage probability to be identical to zero. In such cases probabilistic treatment of more controlling parameters has to be implemented (and fracture considered) in order to generate reliable probabilistic results.

For case BWR2 it takes more than 40 years before leakage probabilities above zero are generated, Figure 8. In the case PWR3 it takes more than 20 years, Figure 9. As soon as leakage probabilities start to be generated, in all cases the probability increases quickly, by more than two decades in five years.

The following results are obtained for the impact of POD simplifications. The 80% detection limit simplified POD is only predicted to result in a smal risk reduction for the case BWR1. The results for the 2 mm detection limit simplified POD follows the SKI POD results, and are up to one decade higher probabilities in the low probability cases. For the case BWR1 the leakage probabilities at 60 years (end-of-life) are within a factor of ten for all three POD curves.

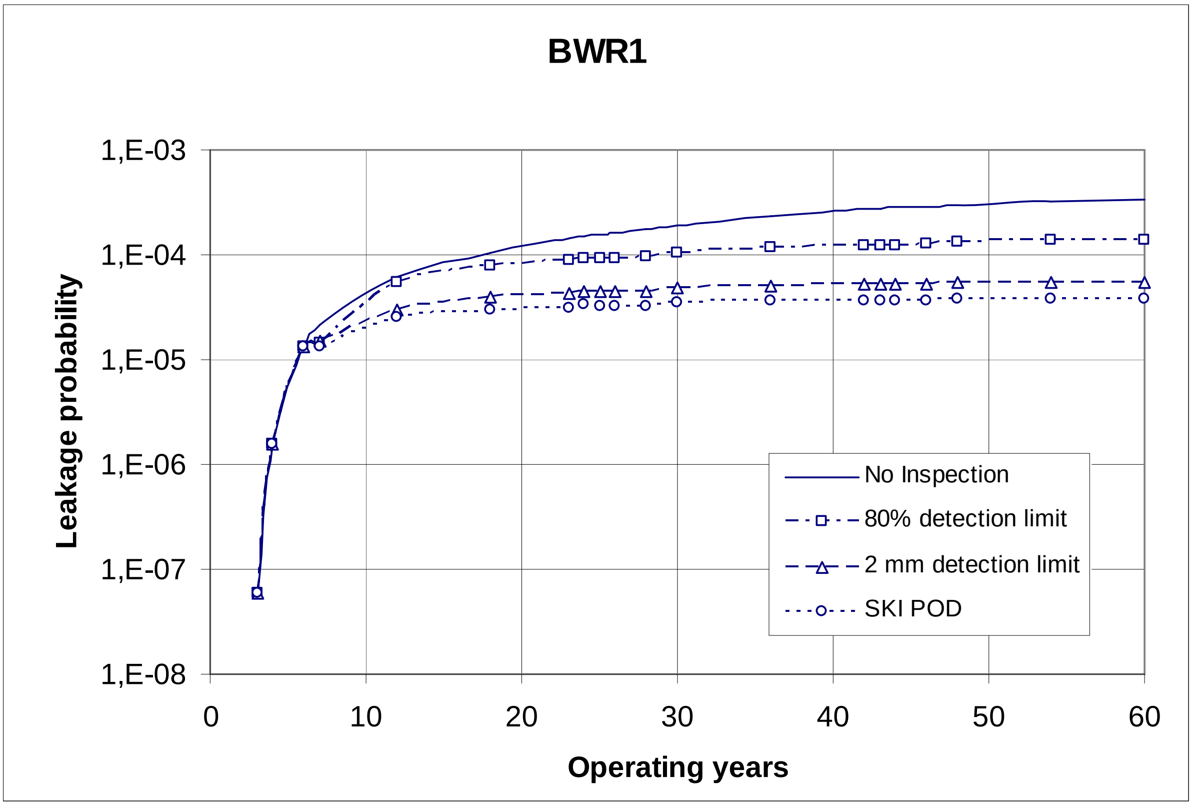


Figure 7 Average leakage probabilities for case BWR 1 from NURBIT.

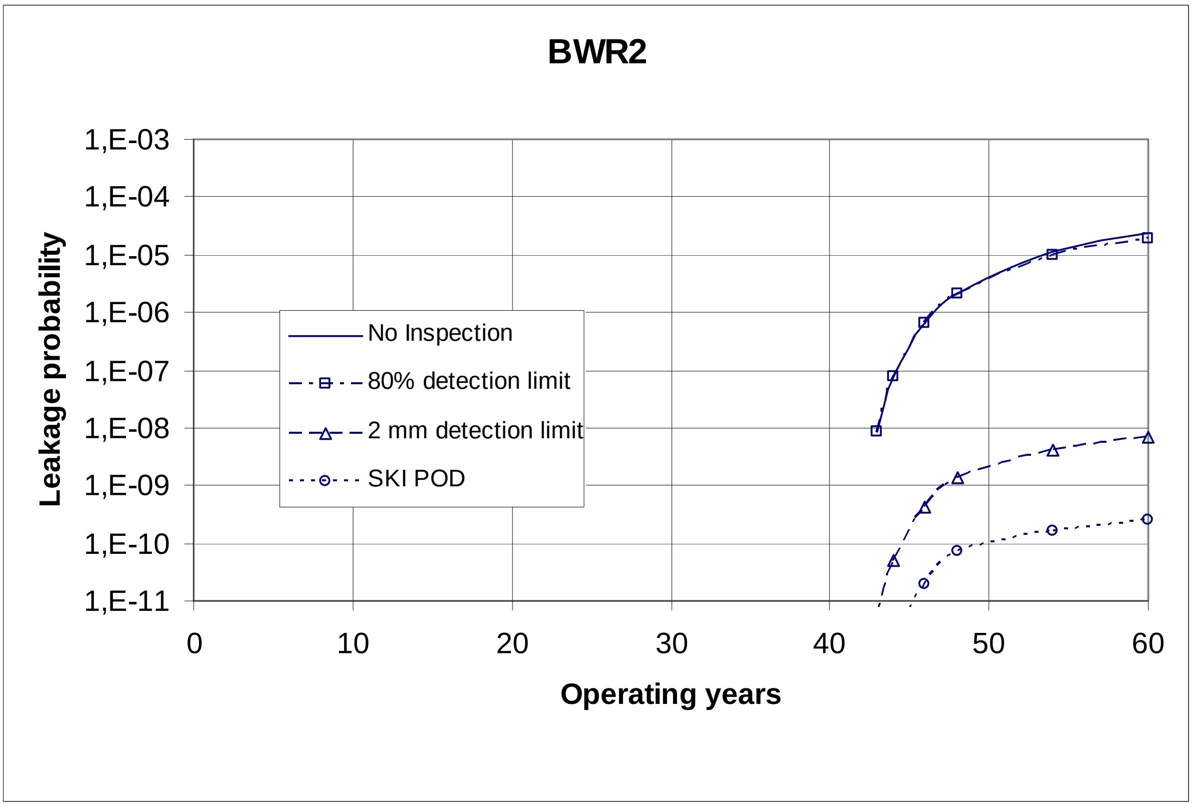


Figure 8 Average leakage probabilities for case BWR 2 from NURBIT.

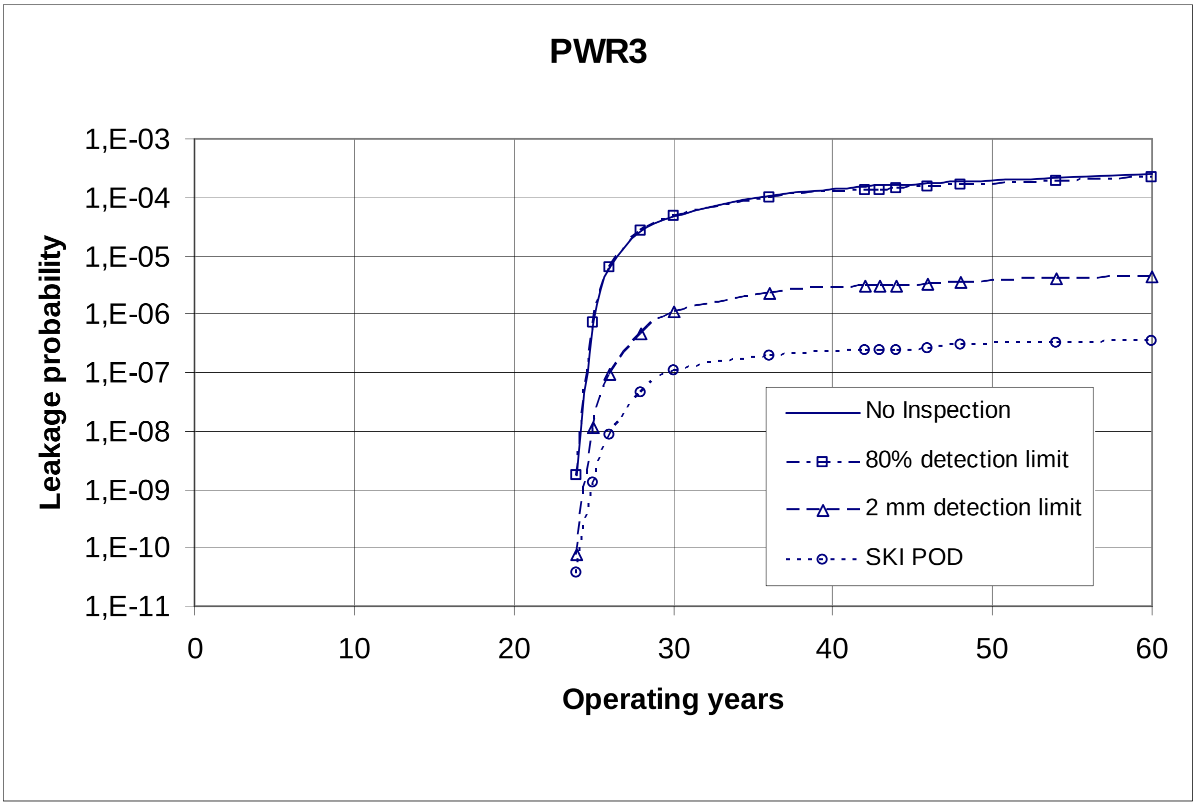


Figure 9 **Average leakage probabilities for case PWR 3 from NURBIT.**

Table 3 is a summary of the NURBIT results for the leak probability at 60 years of operation. The probabilities are the average for the last 6 years (over the inspection interval). The risk reduction obtained for the SKI POD and the 2 mm limit simplified POD is of the same order. The relative risk reduction is very high for case BWR2 and PWR3, but a bit more moderate for the high probability case BWR1. The relative risk reduction using the 80% detection limit POD curve is low or very low.

Table 3 **Summary of NURBIT results**

	Inspection	Last 6 years average	RRF	R
BWR1	SKI POD 2 mm detection limit 80 % detection limit No Inspection	3,861E-05 5,541E-05 1,398E-04 3,375E-04	9 6 2	89 % 84 % 59 %
BWR2	SKI POD 2 mm limit 80 % limit No Inspection	2,449E-10 6,757E-09 1,955E-05 2,425E-05	99020 3589 1	100 % 100 % 19 %
PWR3	SKI POD 2 mm limit 80 % limit No Inspection	3,477E-07 4,383E-06 2,123E-04 2,500E-04	719 57 1	100 % 98 % 15 %

5.1.3 JRC results

Figures 10 to 12 show the yearly failure probabilities results from the JRC approach. As described in section 4.2 the event of leakage was approximated in the JRC model as when the crack has advanced to 80% of the wall thickness. For this reason results for the 80% limit POD curve is not presented for the JRC approach. A summary of the JRC analyses is presented in Table 4.

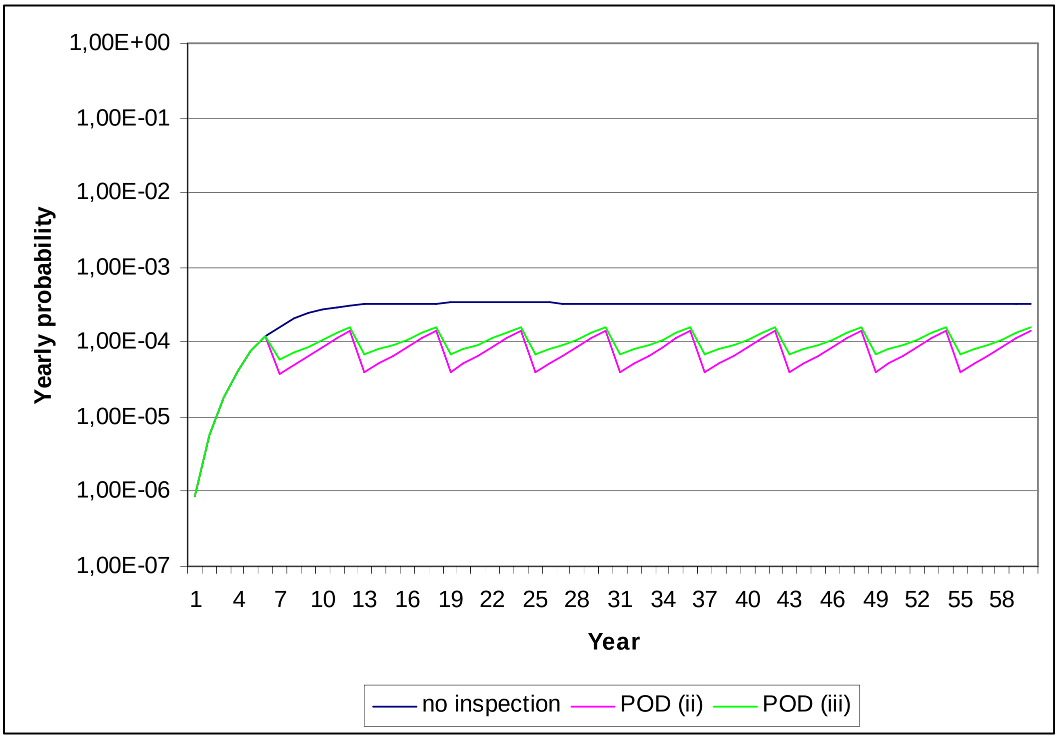


Figure 10 **JRC analysis of case BWR1 showing the yearly probability of leakage. POD (ii) is the SKI POD curve, and POD (iii) is the 2 mm limit curve.**

Figure 11 **JRC analysis of case BWR2 showing the yearly probability of leakage. POD (ii) is the SKI POD curve, and POD (iii) is the 2 mm limit curve.**

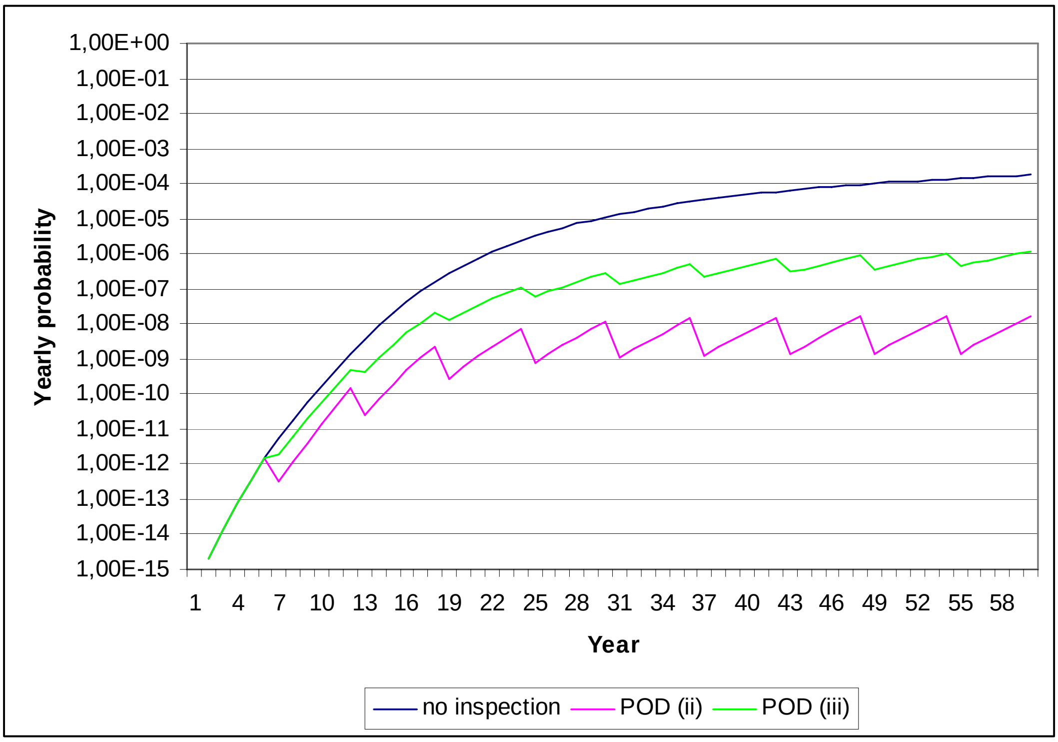


Figure 12 **JRC analysis of case PWR3 showing the yearly probability of leakage. POD (ii) is the SKI POD curve, and POD (iii) is the 2 mm limit curve.**

Table 4 Summary of JRC analysis results.

	Inspection	Last 6 years average	RRF	R
BWR1	SKI POD 2 mm detection limit 80 % detection limit No Inspection	8,30E-05 1,07E-04 - 3,31E-04	4 3 -	75 % 68% -
BWR2	SKI POD 2 mm limit 80 % detection limit No Inspection	5,63E-08 3,02E-07 - 5,03E-05	89 17 -	99 % 94% -
PWR3	SKI POD 2 mm limit 80 % detection limit No Inspection	6,75E-09 7,66E-07 - 1,58E-04	23479 207 -	100 % 100% -

5.1.4 Inspecta ProSACC results

The ProSACC probabilistic module was used to analyse the cases only without inspections.

For case BWR1, a complete circumferential crack will have a critical depth which is equal to 77% of the wall thickness. This means that it is possible to define a critical event using ProSACC. But, at year zero the most probable point of failure is larger than 80% of the wall thickness. Therefore, ProSACC can not be used in this case.

For the BWR2 case, it is impossible to achieve a critical event using ProSACC. This has to do with the fact that very long cracks (up to a complete circumferential crack) will have a critical depth which is larger than 80% of the wall thickness.

Concerning case PWR3, the main difference between the results from ProSACC and NURBIT is related to the assumptions regarding crack depth. ProSACC treats this as a probabilistic parameter and NURBIT has a deterministic assumption. Using assumptions simlar to NURBIT, together with the data (loads, material etc), it is impossible to get any leakage event until the crack has been growing for approximately 22 to 25 years.

5.2 Comparison of results from different approaches

In this section the results from the different structural reliability approaches are compared with focus on the effect of inspections on the estimated leakage probabilities. This benchmarking of different approaches can provide added confidence on the modelling, help identify further development needs and reveal critical model properties for evaluating these cases.

First the VTTBESIT results are compared to the NURBIT results in section 5.2.1, and then the VTTBESIT results are compared to the JRC results in section 5.2.2. As discussed in section 4.2 the different approaches use different approximations for the event of leakage; VTTBESIT use crack depth 100% of the wall thickness, NURBIT use 90 % and the JRC approach use 80 %. As the crack growth is rapid during the final stage of wall penetration, this approximation is not expected to be decisive for the differences in the results between the approaches. Other differences in the models described in section 3 are expected to have larger influence. However, since the VTTBESIT method quite easily can produce probabilities for both 100% and 80% of wall thickness penetration, the VTT results were chosen as basis for the comparisons, in order to exclude the effect of the difference in the approximation of the leak event. This effect may be studied by comparing the VTTBESIT results in section 5.2.1 and section 5.2.2.

The analysis results were compared using the following descriptive measures:

- Average yearly failure probability
- Last 6 years average yearly failure probability
- Risk reduction factor
- Risk reduction percentage

The values for these measures were calculated for each of the POD functions as well as for no inspections.

5.2.1 Comparison between VTTBESIT and NURBIT results

The VTTBESIT and NURBIT results are compared in Table 5 and Figures 13-15. The average (over the inspection interval, 6 years) leakage probability for three POD-curves and "no inspections" after 60 years of operation is compared. The comparison shows that the difference between the VTTBESIT and NURBIT results is very small for "no inspections". Table 6 shows a comparison of the absolute values and factorial differences between the two approaches.

The NURBIT results show a larger influence of the difference between the three cases for the SKI POD compared to the VTTBESIT results. At the same time the results are similar for "no inspections", and this could indicate that a main cause for the difference is the difference in the inspection model.

Table 5 Comparison of VTTBESIT and NURBIT results

		VTT			Inspecta		
Case	**Inspection**	**Last 6 years average**	**RRF**	**R**	**Last 6 years average**	**RRF**	**R**
BWR1	SKI POD 2 mm detection limit 80% detection limit No inspections	1,22E-06 2,73E-06 5,19E-05 2,34E-04	192 86 5	99 % 99 % 78 %	3,85E-05 5,53E-05 1,40E-04 3,38E-04	9 6 2	89 % 84 % 59 %
BWR2	SKI POD 2 mm detection limit 80% detection limit No inspections	5,70E-07 9,71E-07 3,66E-05 5,52E-05	97 57 2	99 % 98 % 34 %	2,34E-10 6,65E-09 1,94E-05 2,42E-05	103289 3637 1	100 % 100 % 20 %
PWR3	SKI POD 2 mm detection limit 80% detection limit No inspections	3,73E-06 1,61E-05 2,47E-04 3,36E-04	90 21 1	99 % 95 % 26 %	2,53E-07 3,88E-06 2,05E-04 2,47E-04	979 64 1	100 % 98 % 17 %

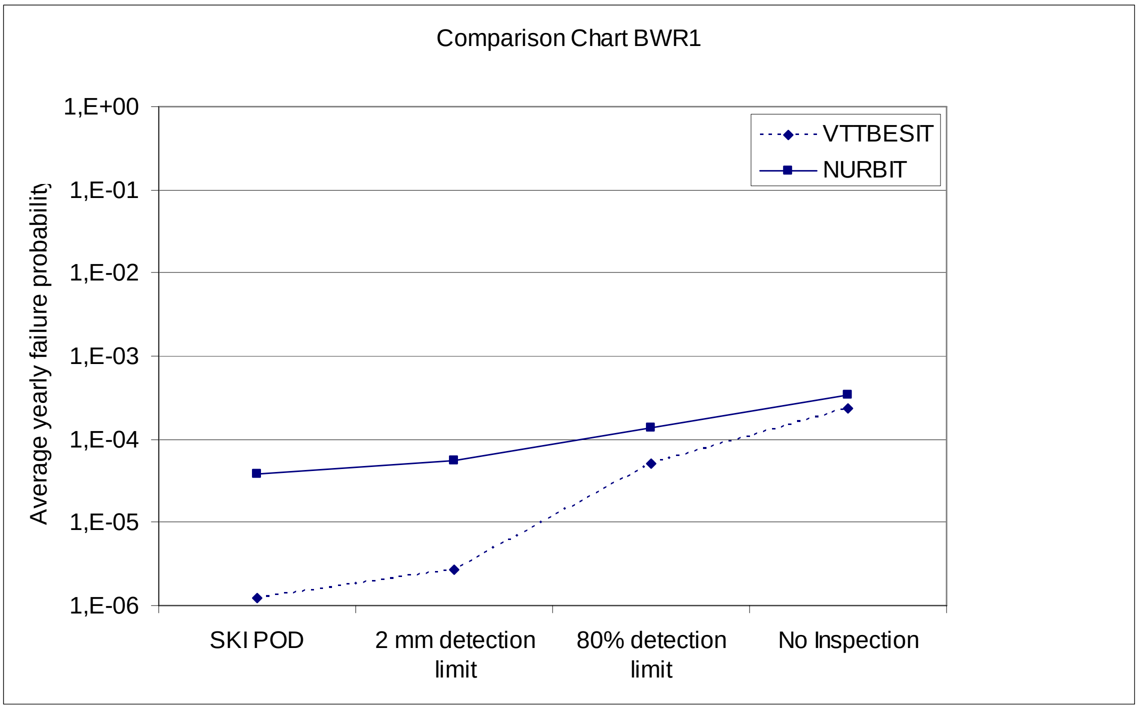


Figure 13 Comparison of the leakage probabilities at 60 years calculated by the VTTBESIT and the NURBIT approaches for case BWR1 for the different POD curves.

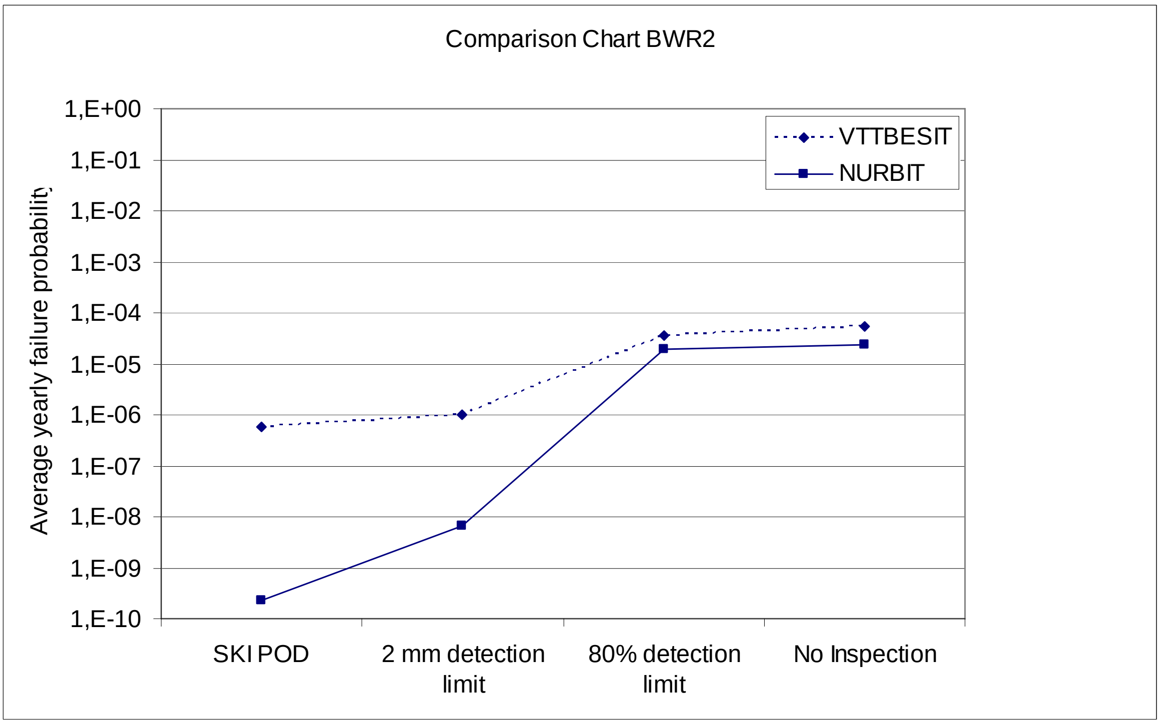


Figure 14 **Comparison of the leakage probabilities at 60 years calculated by the VTTBESIT and the NURBIT approaches for case BWR2 for the different POD curves.**

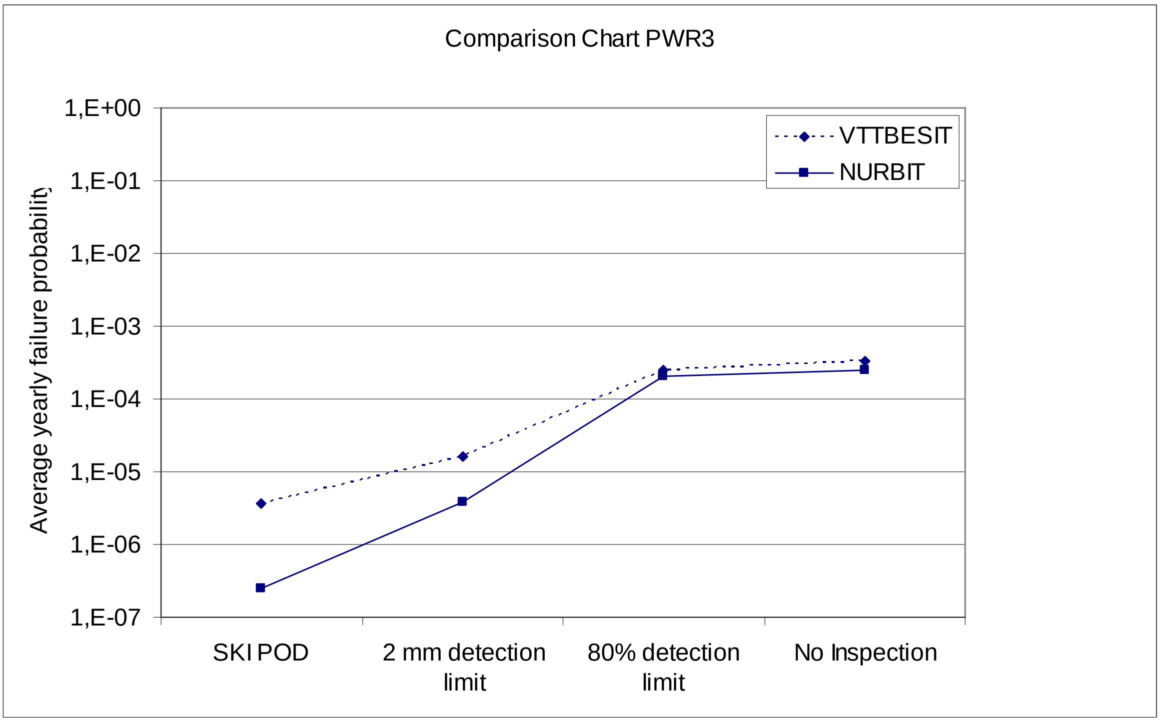


Figure 15 **Comparison of the leakage probabilities at 60 years calculated by the VTTBESIT and the NURBIT approaches for case PWR3 for the different POD curves.**

The VTTBESIT curve in Figure 13-15 show small variations between the three cases, and VTT show about the same RRF in all cases. The NURBIT results show larger influence of the difference in the parameters between the cases.

Table 6 Comparison of VTTBESIT and NURBIT absolute values

		VTT	Inspecta	
Case	**Inspection**	**Last 6 years average**	**Last 6 years average**	**Factor** (*)
BWR1	SKI POD	1,22E-06	3,85E-05	1/31,5
	2 mm detection limit	2,73E-06	5,53E-05	1/20,3
	80% detection limit	5,19E-05	1,40E-04	1/2,7
	No inspections	2,34E-04	3,38E-04	1/1,4
BWR2	SKI POD	5,70E-07	2,34E-10	2434,4
	2 mm detection limit	9,71E-07	6,65E-09	146,0
	80% detection limit	3,66E-05	1,94E-05	1,9
	No inspections	5,52E-05	2,42E-05	2,3
PWR3	SKI POD	3,73E-06	2,53E-07	14,8
	2 mm detection limit	1,61E-05	3,88E-06	4,1
	80% detection limit	2,47E-04	2,05E-04	1,2
	No inspections	3,36E-04	2,47E-04	1,4

(*) Note: the Factor is calculated as f(VTT)/f(Inspecta)

5.2.2 Comparison between VTTBESIT and JRC results

Table 7 show the last 6 years average 80% penetration probabilities, risk reduction factors and risk reduction percentages for VTTBESIT and JRC analyses. The yearly probabilities for a crack reaching 80% of wall depth for the three cases are presented in Figures 16-18.

VTT results for 80% of wall thickness penetration are based on the calculations for the normal analysis (100 % wall thickness), with the yearly leakage probabilities being changed to yearly probabilities for cracks surpassing 80% of wall thickness. This was calculated by changing the Markov model states corresponding to 80-100% wall thickness into absorbing states.

It can be seen that for cases with no inspections the frequencies for crack to reach 80 % of wall thickness (approximation of leak) are quite similar in JRC and VTT analyses for the cases BWR1 and PWR3, and the difference for case BWR2 is about a factor of ten. The difference between VTT and JRC analyses is similar to the difference between VTT and NURBIT results: the VTTBESIT probabilities for cases BWR2 and PWR3 are higher, especially when the inspections are taken into account. The VTTBESIT values are about one order of magnitude higher than those calculated by JRC. Again, for the case BWR1 the results without inspections are very close to each other, but VTTBESIT values are lower when inspections are modelled.

Table 7 Last 6 years average 80% penetration probabilities, risk reduction factors and risk reduction percentages summary table for VTTBESIT and JRC analyses.

		VTT	RRF	R	JRC	RRF	R
BWR1	SKI POD	1,02E-05	37	97 %	8,30E-05	4	75 %
	2 mm detection limit	1,60E-05	24	96 %	1,07E-04	3	68 %
	No inspections	3,76E-04			3,31E-04		
BWR2	SKI POD	9,49E-07	66	98 %	5,63E-08	89	99 %
	2 mm detection limit	1,41E-06	44	98 %	3,02E-07	17	94 %
	No inspections	6,22E-05			5,03E-06		
PWR3	SKI POD	7,34E-06	47	98 %	6,75E-09	23479	100 %
	2 mm detection limit	2,16E-05	16	94 %	7,66E-07	207	100 %
	No inspections	3,42E-04			1,58E-04		

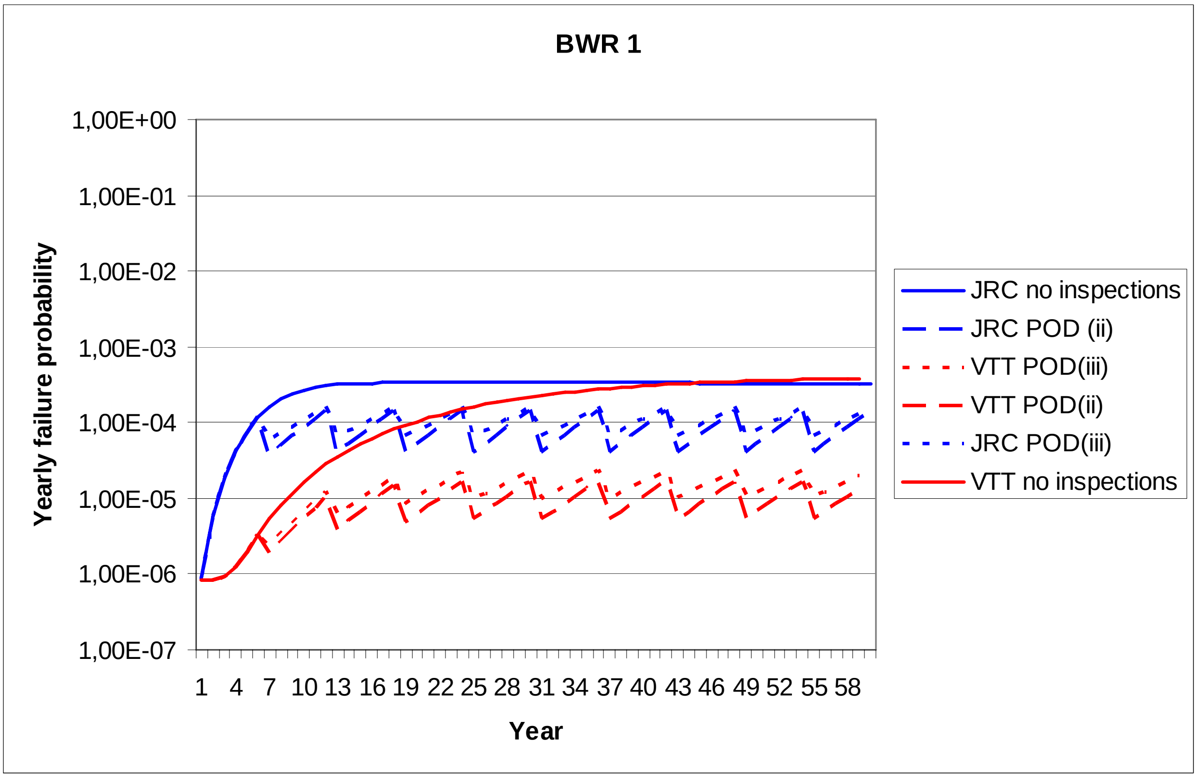


Figure 16 Comparisons of the yearly probabilities for a crack reaching 80% of wall depth for the case BWR1. POD(ii) = SKI POD, POD (iii) = 2mm detection limit.

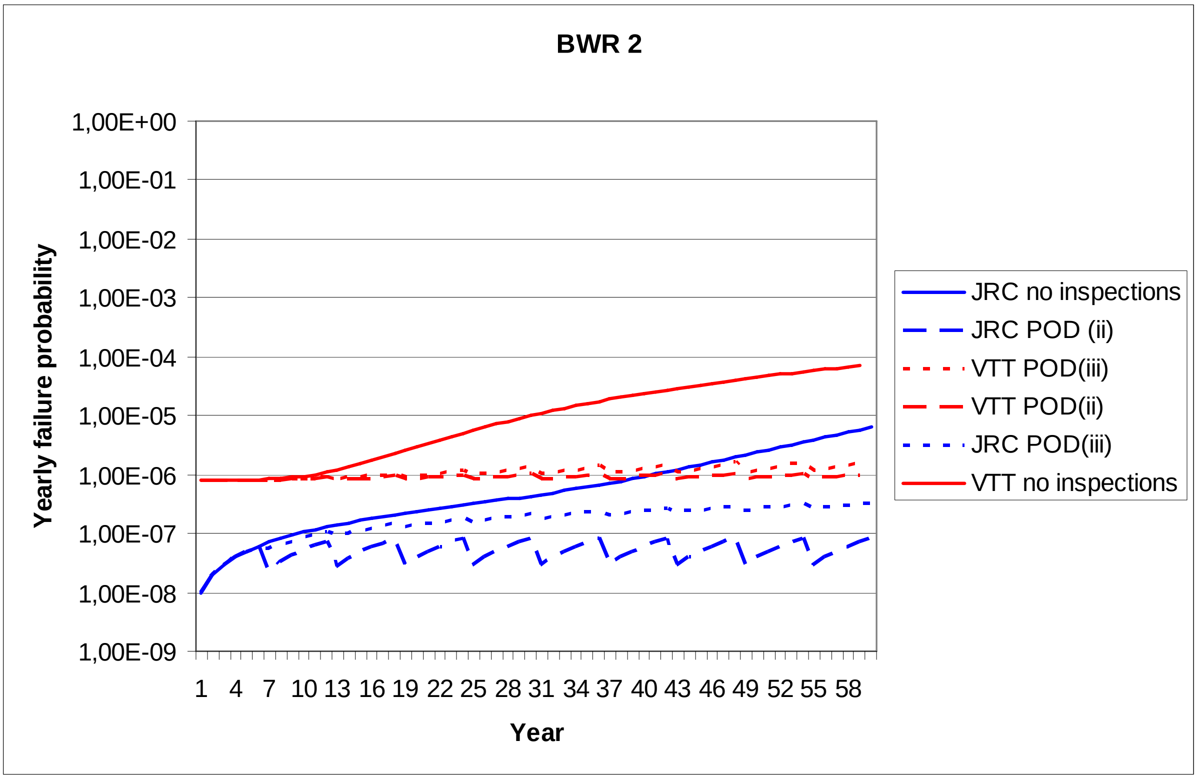


Figure 17 **Comparisons of the yearly probabilities for a crack reaching 80% of wall depth for the case BWR2. POD(ii) = SKI POD, POD (iii) = 2mm detection limit.**

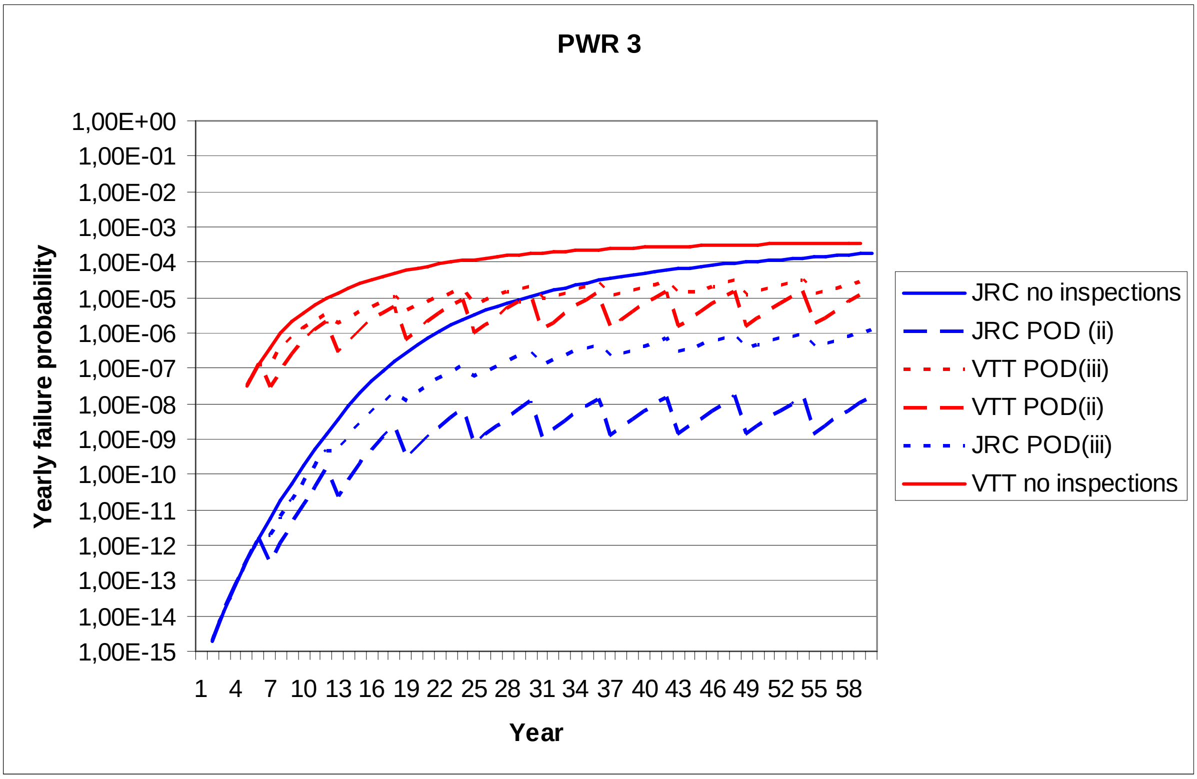


Figure 18 **Comparisons of the yearly probabilities for a crack reaching 80% of wall depth for the case PWR3. POD(ii) = SKI POD, POD (iii) = 2mm detection limit.**

5.3 Sensitivity analyses

Two variables were selected for the sensitivity analyses: (i) initial crack depth distribution, and (ii) inspection interval. The sensitivity to crack depth distribution was analysed by varying the expected value of the probabilistic distribution of the initial cracks depth. The expected values used were 50% and 200% of the baseline distribution. The influence of the inspection intervals was analyzed for 1, 6 (baseline) and 10 year intervals.

Detailed results of the sensitivity analyses are shown in Appendix B for the VTTBESIT, NURBIT and JRC approaches. These results consist of leakage probability figures for the sensitivity analyses and summary tables with last six years average yearly failure probability, the risk reduction measures and percentage of the last six years average when compared to the baseline case. The results are given for both no inspections and the SKI POD cases. The JRC results are calculated for crack growth until 80 % of wall thickness, NURBIT until 90% and VTTBESIT until 100%.

5.3.1 Sensitivity to initial crack depth

Figures 19-21 show the NURBIT results for the sensitivity of the leakage probability to the initial crack depth.

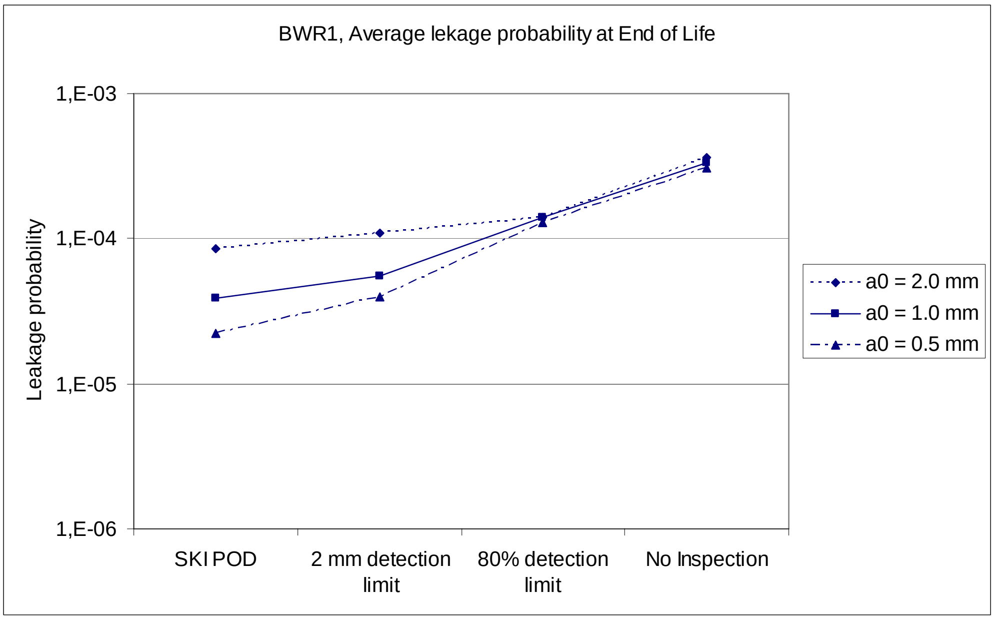


Figure 19 Sensitivity to assumed initial crack depth, BWR1 (NURBIT results).

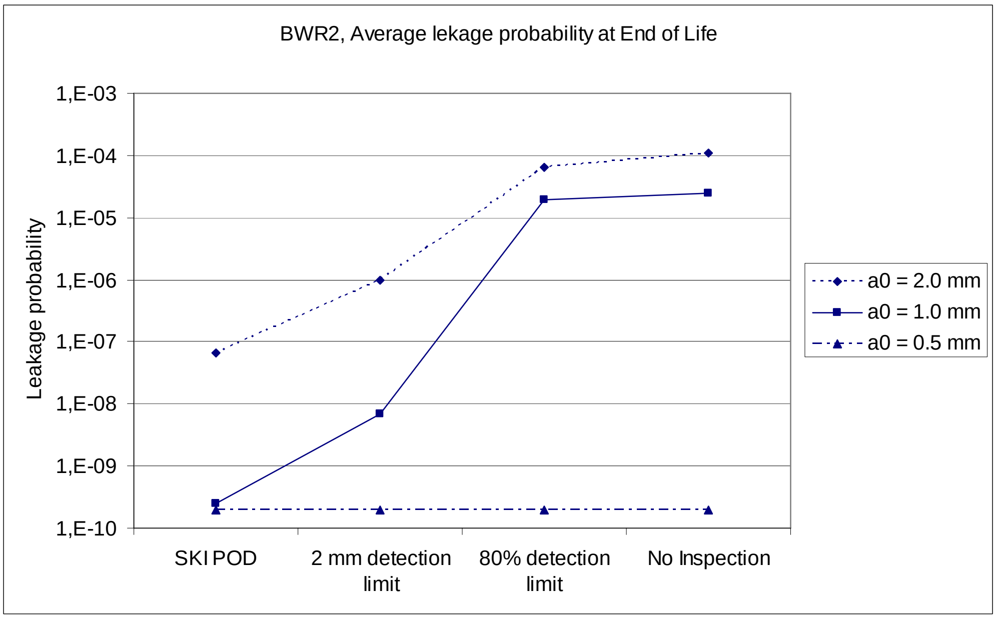


Figure 20 **Sensitivity to assumed initial crack depth, BWR2 (NURBIT results).**

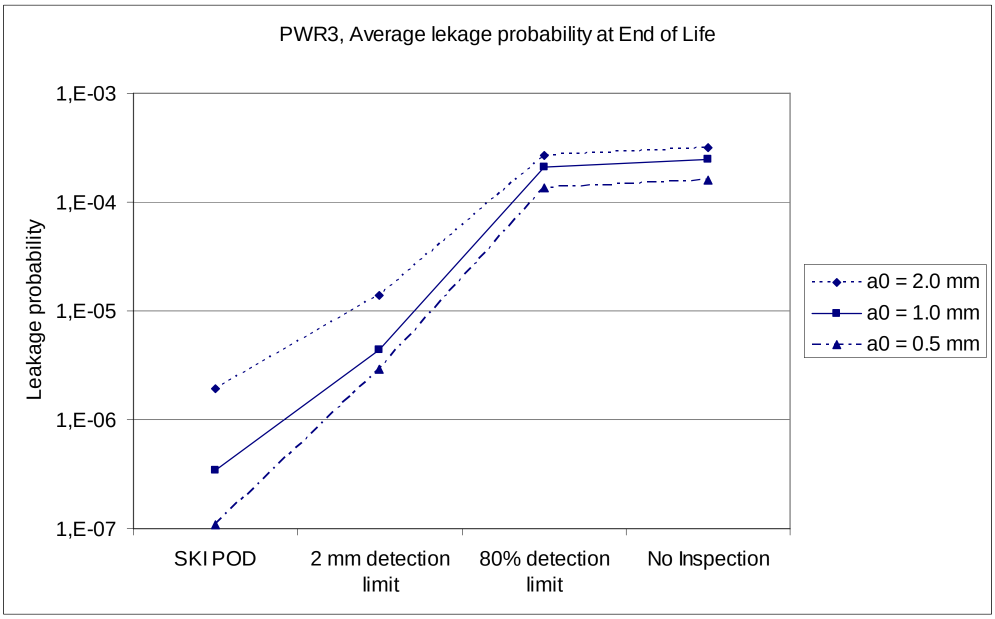


Figure 21 **Sensitivity to assumed initial crack depth, PWR3 (NURBIT results).**

For case BWR1 and PWR3 the sensitivity of the NURBIT results to the assumed initial defect depth is reasonable and the influence follows the expected trend. The results for the very low stress and low probability case BWR2, are very sensitive to the assumed initial defect depth. When an initial defect size of 0.5 mm is assumed for this case, no results are obtained from NURBIT and a cut-off value of 10^{-10} is applied.

When compared to VTTBESIT results, following observations can be made. Contrary to the NURBIT results, in case BWR1 the calculated yearly failure probabilities are lowest for the largest initial crack depth distribution. The explanation suggested for this initially counterintuitive result is the following: since the initial crack length distribution has remained unchanged, the length / depth ratio of the cracks decreases. This ratio has an large influence on the stress intensity at the crack tip, causing decrease in the crack growth speed. The same behavior is seen in the results from the JRC approach. In NURBIT the crack length is a probabilistic parameter, but the crack depth is a deterministic parameter.

For the case BWR2, the results for the initial crack depth distribution 200 % of the baseline without inspections are in relatively good agreement between VTTBESIT, NURBIT and JRC. In this case, the depth distribution has a notable effect on the leak probability. When the crack depth are assumed smaller (expected value 50 % of the baseline value), the results show large variation.

In the case BWR3, the results of all analysis teams agree that the effect of crack depth is relatively small in the case without inspections. When the inspections are taken into account, the VTTBESIT results and the JRC results indicate a relatively small effect of the assumed crack depth distribution. The NURBIT results in a bit larger influence of the initial crack depth assumption.

5.3.2 Influence of inspection interval

Figures 22-24 show the NURBIT results for the sensitivity of the leakage probability to inspection interval. The risk reduction is very high when using a 1-year inspection interval, for the SKI POD and the 2 mm limit simplified POD, two decades for the high probability case BWR1. The relative risk reduction using the 80% detection limit POD curve is low even with a 1-year interval. The relative change in leakage probability between 6-years and 10-years interval is small for the high probability case BWR1, and larger for the low probability cases BWR2 and PWR3.

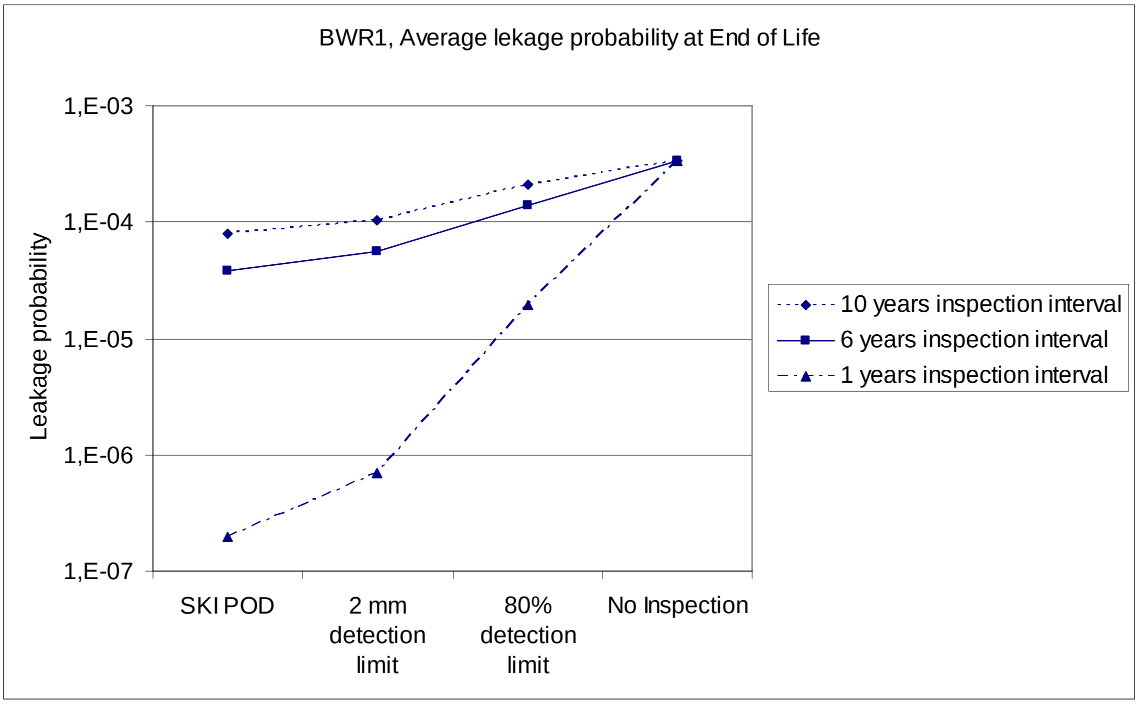


Figure 22 **Influence of inspection interval for different POD curves, BWR1 (NURBIT results).**

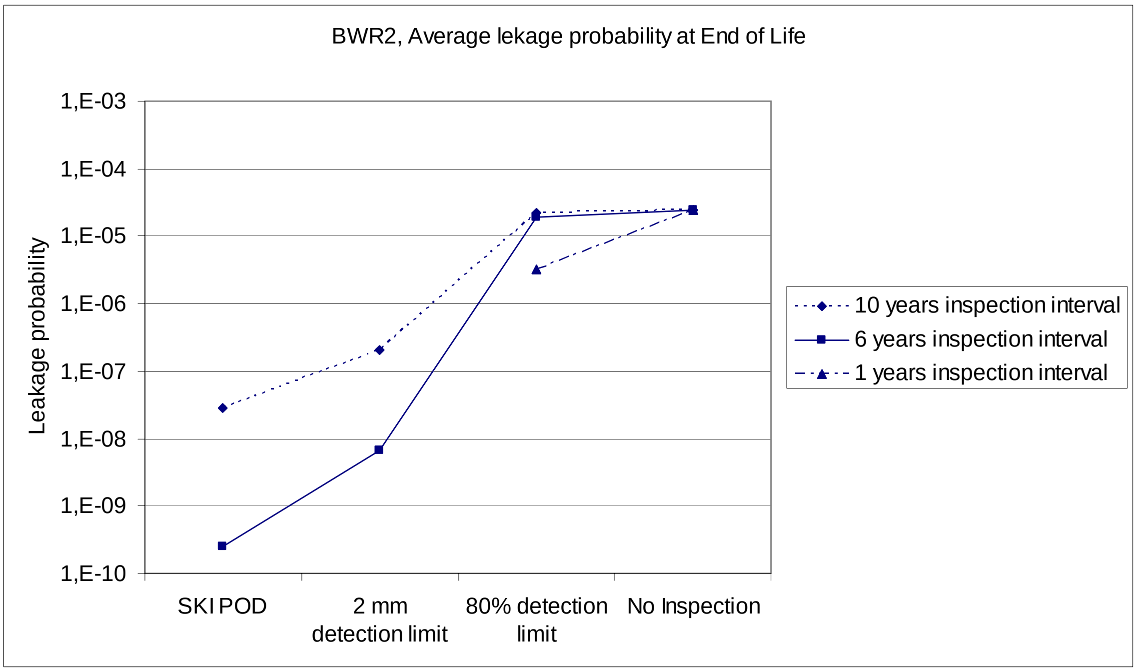


Figure 23 **Influence of inspection interval for different POD curves, BWR2 (NURBIT results).**

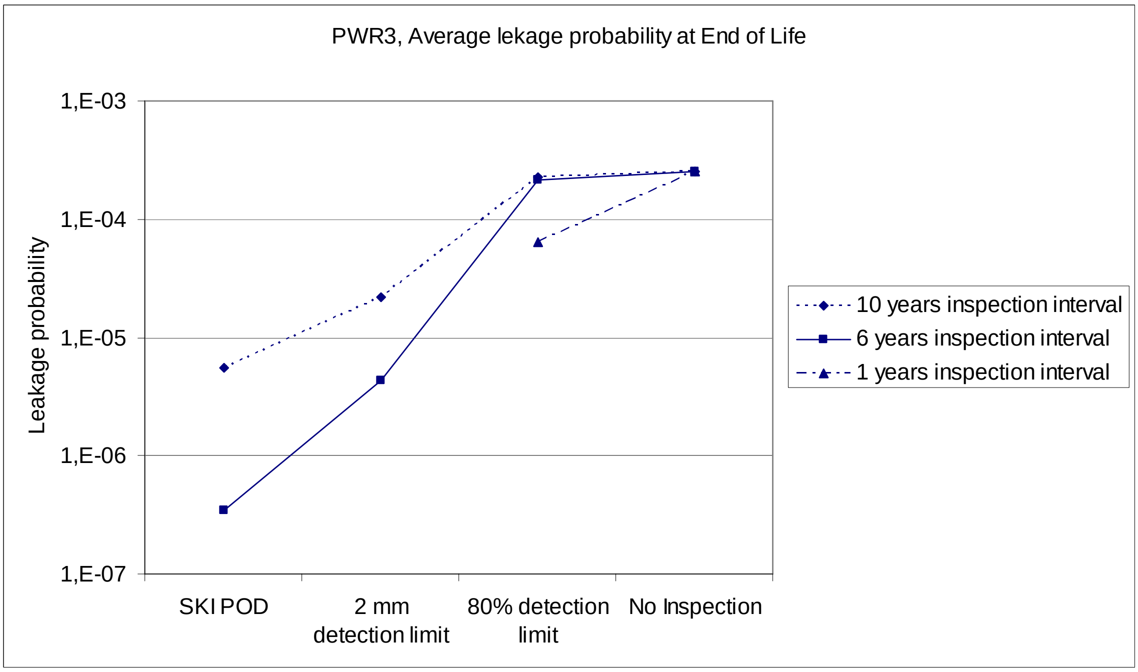


Figure 24 **Influence of inspection interval for different POD curves, PWR3 (NURBIT results).**

The influence of the inspection interval predicted by the different approaches is presented in Table A2 (VTTBESIT), Table A4 (NURBIT) and Table A6 (JRC) in Appendix 2. The inspection interval has a large effect on the leakage probability, especially when comparing 1-year intervals to the 6-year interval. The same trend is seen from all three approaches, even if the absolute numbers differ. When the SKI POD and 2mm detection limit POD were used in NURBIT with 1-year inspection intervals, for cases BWR2 and PWR3 the failure probabilities fell below the cut-off limit in NURBIT.

The increase of the inspection interval from 6 to 10 years with SKI POD assumption increases the failure probability by a factor of 2-5 for BWR1 depending on the analysis group. For the two other low probability cases, the differences between analysis groups are larger.

5.4 Additional capabilities of the calculation tools

In a benchmark, only features common to different analysis tools can be compared. Limitations of some tools cause that some interesting features or capabilities of other tools cannot be reviewed. In this section, we discuss some capabilities of the individual tools.

The NURBIT code has the capability to evaluate the development of a through wall crack to rupture, and account also for leak detection. Further, upset loads can be analysed. These features were applied to the piping cases analysed in this study, and some results are presented in 5.4.1.

The JRC approach could in principle randomise rather easily other parameters than those assumed random in this study. Obviously the more parameters are modelled with distributions, the heavier the analyses become and calculations can take a very long time.

ProSACC could introduce randomise parameters other than those assumed random in this study. However, when other methods than MCS are used for numerically efficient calculations, the introduction becomes a bit complicated.

The development of VTTBESIT has recently focused on widening the scope of the tool to include several degradation mechanisms. An example of fatigue is presented in section 5.4.2.

5.4.1 NURBIT – influence of upset loads, fracture and leak detection reliability

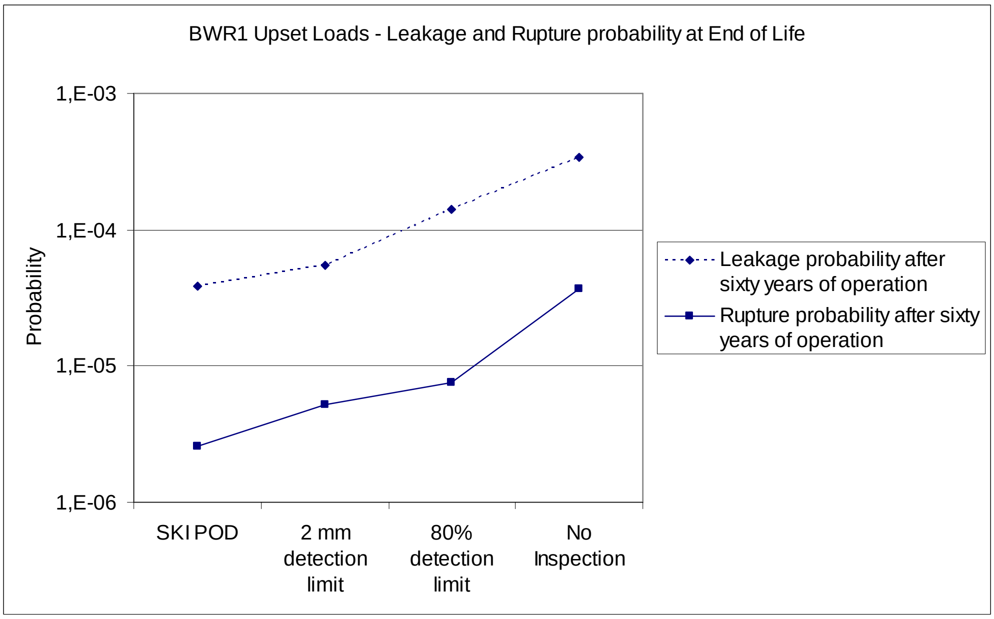
As described in section 3.1 NURBIT is based on a very detailed and complete deterministic fracture mechanical model that describes most possible events during degradation and failure of piping due to crack growth; from initiation, crack growth, wall penetration and leakage, the possibility for rupture (fracture or plastic collapse) due to upset loads that occur each year, leak rate detection evaluation, and time margin to final fracture at LBB.

In the previous benchmark cases in this report, leakage at the welds is analysed analysing only stress corrosion crack growth at normal operation conditions. In this section we will illustrate some additional analysis capabilities in the NURBIT analysis tool, and also explain the importance of the very complete fracture mechanical model in NURBIT.

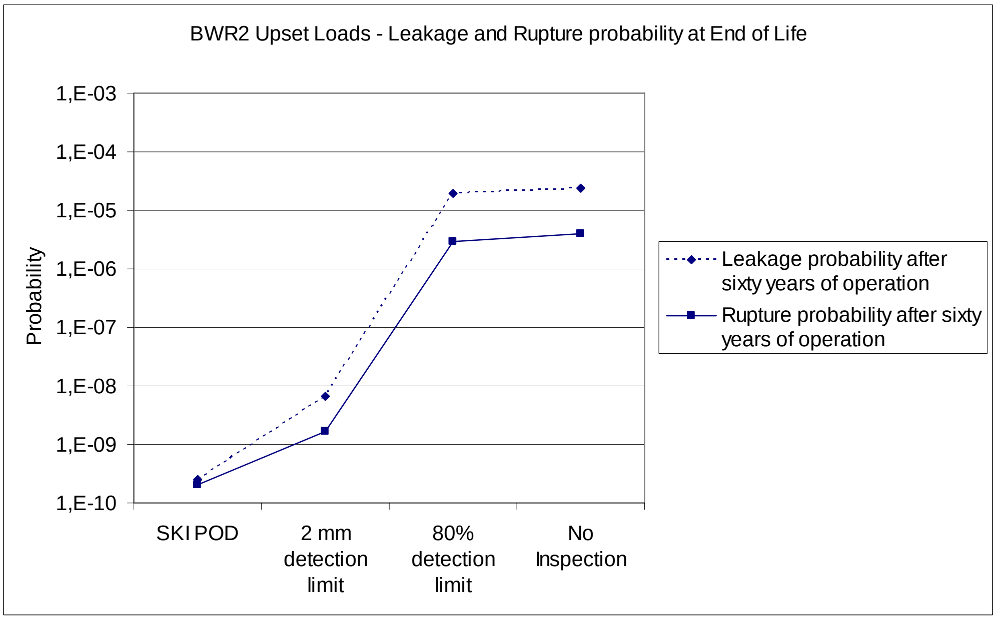
When load events in addition to the normal operation loading are considered, fracture is likely to occur even before wall penetration. For example the safety relief valves are tested regularly and this upset load case is expected to occur each year. The magnitude of the upset load was taken from [3] for the cases BWR1 and PWR3, and a typical value was chosen correspondingly for BWR2. The leak rate detection limit was set to the same low value as in the previous analyses, 0.1 kg/s (virtually all leaks are detected). Figure 25 shows the results from NURBIT when this upset load is included and the rupture probability is calculated in addition to the leakage probability. The example illustrates that the rupture probability is not negligible when upset loads are considered.

The importance of considering the upset loads and the rupture probability is highlighted if an evaluation of the risk is made. For risk evaluations the calculated probabilities are combined with consequences; the conditional core damage probability (CCDP). The CCDP for LOCA is assumed in the case of pipe rupture (or a very large leakage), and for a small leakage it is assumed that the CCDP for a normal shutdown of the plant is representative.

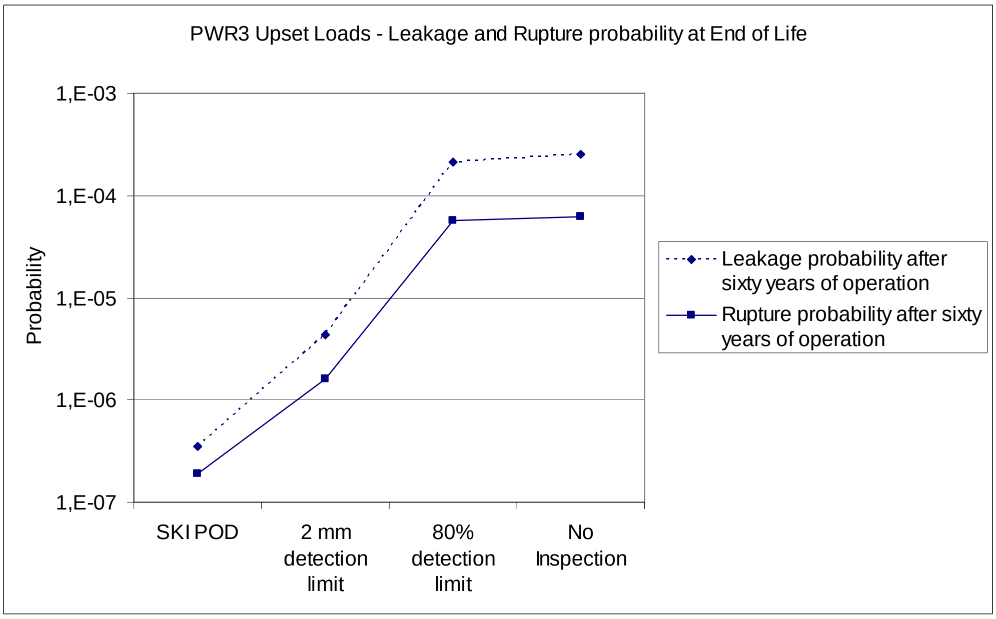
Consider the example in Figure 25. If the consequence of pipe rupture is just 10 times higher than the consequence for leakage, then the dominating risk is due to the probability of pipe rupture. Usually the difference in CCDP between rupture and leakage can actually be a factor of 1000, and this shows the importance of also including the evaluation of pipe break probabilities in the models.



(a) NURBIT results for leakage and rupture probability for a regular upset load, case BWR1.



(b) NURBIT results for leakage and rupture probability for a regular upset load, case BWR2.



(c) NURBIT results for leakage and rupture probability for a regular upset load, case PWR3.

Figure 25 **Results from NURBIT including analysis of both leakage probability and rupture probability when a regular upset load is considered. (a) BWR1, (b) BWR2 and (c) PWR3.**

Further, for the leakage to result in a forewarning event, the leak rate from the penetrating crack has to be large enough to be detectable by the plant leak monitoring systems (well in advance before the crack reaches critical size for fracture). Studies have shown that neglecting the effect of leak detection in the assessment of probability of failure may cause an unjustified focus on low-risk components for inspection selection. In the benchmark cases in this report leakage was assumed immediately when the crack penetrates the wall, and it was assumed that very small leak rates are detectable – in order to compare with the other models. However, the influence of realistic leak detection capabilities can also be evaluated by use of the NURBIT model.

5.4.2 VTTBESIT – evaluation of several degradation mechanisms

The VTTBESIT code was first developed to analyse stress corrosion crack propagation. Later the capabilities have been extended to allow probabilistic modelling of also other degradation mechanism, such as thermal fatigue and low-cycle fatigue.

We present here a case with thermal fatigue in a mixing point of cold and hot water. In the case of thermal fatigue induced cracking it is typical that a crack either grows very fast or hardly at all. Due to this, inspections with several years' interval are not very efficient to reduce the failure probability. In the analysed case two step function PODs were considered. Both of them had the step at 20 % of wall thickness, and POD below this was zero. One had 0,9 POD for cracks exceeding 20% of the wall thickness, and for the other the POD was 0,65.

Figure 26 illustrates the development of yearly failure probabilities without inspections and with inspections at 10 year interval considering the two inspection capabilities. Yearly failure probabilities for the two POD cases are almost identical despite one having much lower probability of detection than the other. The risk reduction is only 12%. In a case like this it is unlikely that an inspection will reveal a crack before it grows through wall.

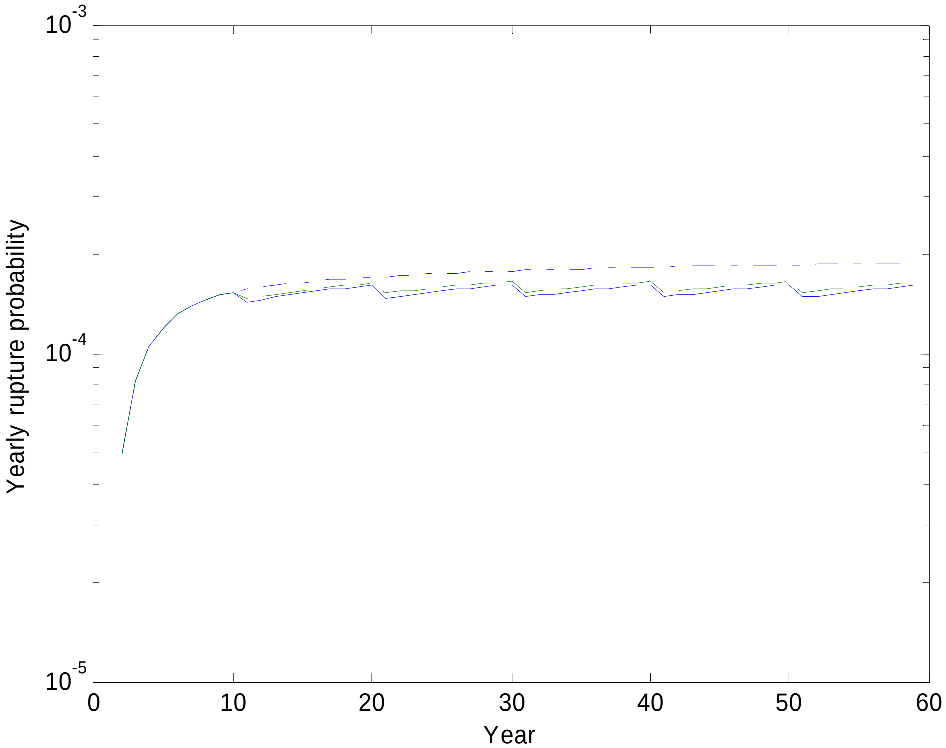


Figure 26 **Illustration of analysis of thermal fatigue with VTTBESIT. Dash-dotted line is without inspections, solid line and dashed line are calculated with inspections at 10 year intervals for POD 0,9 and 0,65 for cracks exceeding 20 % of wall thickness.**

6 DISCUSSION AND CONCLUSIONS

The study had two main aims. The first aim was to study the effect of POD assumptions on failure probability using structural reliability models. The main interest was to investigate whether it is justifiable to use a simplified POD curve. The second aim was to compare various structural reliability calculation approaches for a set of cases. Through benchmarking one can identify differences and similarities between modelling approaches, and provide added confidence on models and identify development needs.

In this study, four different structural reliability approaches were applied: VTTBESIT at VTT, ProSACC and NURBIT at Inspecta and a Matlab based MCS tool at JRC. As the ProSACC tool does not contain the possibility to analyse the effect of inspections, it was only used to evaluate a few cases without inspections. The failure event investigated was leakage (through wall crack), since only NURBIT has the capability to evaluate the leak rate and the probability of rupture for the growing and leaking crack.

In order to investigate the effect of POD assumptions, especially the use of a simplified POD, on the leakage probability, three different PODs were selected for the analyses. The failure probabilities calculated by using two simplified POD curves were compared to results obtained by using a more detailed POD function. Further, structural analyses were run assuming that no inspections are performed. The analysed piping welds all had stress corrosion cracking as the degradation mechanism, and the cases were selected to cover a range of pipe thicknesses, but arbitrary with respect to the other parameters (material properties and loading conditions). Only normal operation load was considered. It is noted that the stresses obtained for the chosen cases are rather low, including the weld residual stress in the cases BWR2 and PWR3.

In order to quantify the risk reduction achieved by inspections, two measures were used. One measure indicates how many percent the risk is reduced from a baseline (e.g. case without inspections). This measure is relatively easy to understand. It's drawback is that for risk reductions over 99%, it may be difficult to perceive the magnitude of a difference between e.g. 99,90 % and 99,99 %. The second measure used was a risk reduction factor indicating how many times smaller the risk is compared to a baseline case. This measure can get very large numbers, eg. if the failure probability is decreased by three orders of magnitude, the factor is 1000. As both of these measures for risk (or failure probability) reduction have their advantages, both of these measures were reported in presenting the results. It was not an objective of this study to develop a rationale for the magnitude of risk reduction that should be achieved by inspections.

The results of the study indicate that the use of a simplified POD curve could be justifiable in RI-ISI applications. All the methods in this study show only relatively small differences between the calculated failure probabilities when using the detailed "full POD" or the simplified step function POD where the step was at 2 mm (assumed detection limit). The differences in risk reduction calculated using the SKI POD and the 2 mm limit POD are in the range of 0 to 5 percentages for each approach.

The other simplified step POD function was defined so that the crack remains undetected until its depth is 80% of the wall thickness. Such low inspection reliability is of course an extremely conservative assumption. With this step POD the effect of inspection is very small and it is not a good approximation of the full POD function. This is not surprising considering that the crack growth is relatively fast in the last 20% of the pipe wall, and this approximation of a step POD is not very useful.

The fact that a 2 mm detection limit is a good approximation of the more detailed SKI POD curve is useful information in RI-ISI applications, since it is less resource intensive to justify a simplified POD. In practice it would suffice to prove that the testing method in question detects cracks of 2 mm size with a certain probability – much more information is needed to develop a full POD curve for any detection method.

The analyses of the three cases in this study reveals that there is a need for a more comprehensive study of the risk reduction due to inspection, systematically covering welds under a range of different loadings and weld residual stresses. The evaluations should preferably include both leakage and rupture. The sensitivity analyses show that in order to identify efficient risk reduction, both the influence of the inspection reliability (POD) and different inspection intervals should be analysed.

The second objective of this study was to benchmark the structural reliability approaches. Comparing the leakage probabilities calculated by VTTBESIT, NURBIT and the JRC approach at the end-of-life (60 years) shows that the results are very similar when inspections are not accounted for. However, when inspections are taken into account the predicted order of magnitude differs. The relative differences between the VTTBESIT approach and the NURBIT approach were largest for SKI POD and 2 mm detection limit simplified POD. The approaches to model the effect of inspections are different in these analysis applications. It is recognised that while the Markov-approach for accounting for inspections used in the VTT method has its advantages in enabling fast analyses of various inspection strategies, the Markov assumption itself may not be fully sound. A more detailed analysis of this issue is needed.

All the applied structural reliability approaches are possible to improve in different areas. It is noted that the NURBIT model has the most complete and accurate deterministic model for describing all the events if a crack develops, including initiation, leakage and fracture, and evaluation of inspection and leak detection reliability. An important feature of the NURBIT model is the continuous evaluation of upset loads, and also leak rates. The weakness is that in the current version very few parameters are evaluated as probabilistic variables. In order for NURBIT to generate probabilistic results also for low probability cases probabilistic treatment of more controlling parameters has to be implemented. This could be balanced against the advantage of a short calculation time, which facilitates sensitivity analyses.

ProSACC uses first order reliability methods in addition to MCS, which is numerically efficient for probabilistic calculations. However, for evaluation of RI-ISI further development of inspection modelling and growth would facilitate application of the tool.

The JRC approach has the most complete probabilistic modelling of the considered approaches. A drawback is that at present the model only considers leakage and do not include all possible events when a crack is growing. Also consideration of non-linear weld residual stress distributions would need introduction of more fracture mechanical solutions. The approach uses rigorous MCS which rather easily allows for randomization of arbitrary model parameters. On the other hand MCS is very time consuming in low probability cases.

VTTBESIT has the possibility to treat several degradation mechanisms (SCC, thermal fatigue, and low-cycle fatigue). Improvements may be introduced in the fracture mechanical models and numerical treatment. Planned improvements include more comprehensive application of crack growth computation over the crack front, refined treatment of weld residual stresses e.g. to take into account how they gradually decrease during the years of operation, and preparing more detailed as well as refined size distribution estimates for initial cracks nucleating during operation due to SCC and fatigue.

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1. GEOMETRY (PIPE AND DEFECT)

1.1 Pipe size (D_y, t).

The pipe size is a deterministic parameter.

BWR1 $\Rightarrow$ $D_y = 114$ mm, $t = 8$ mm

BWR2 $\Rightarrow$ $D_y = 323.85$ mm, $t = 25$ mm

PWR3 $\Rightarrow$ $D_y = 871.5$ mm, $t = 64.85$ mm

1.2 Defect depth distribution (f_a).

The defect depth can be a deterministic or a probabilistic parameter (dependent of the different assumptions in the software). For a probabilistic parameter, following lognormal distributions are used. If defect depth is deterministic, the mean values (μ_a) are used.

BWR1 $\Rightarrow$ f_a = lognormal, $\mu_{LogNor} = 0.9933$, $\sigma_{LogNor} = 0.1784$
$\mu_a = 2.743$ mm, $\sigma_a = 0.4934$ mm

BWR2 $\Rightarrow$ f_a = lognormal, $\mu_{LogNor} = 0.8179$, $\sigma_{LogNor} = 0.3672$
$\mu_a = 2.424$ mm, $\sigma_a = 0.9209$ mm

PWR3 $\Rightarrow$ f_a = lognormal, $\mu_{LogNor} = 0.3434$, $\sigma_{LogNor} = 0.4993$
$\mu_a = 1.597$ mm, $\sigma_a = 0.8497$ mm

1.3 Defect length distribution (f_l).

The defect length should be a probabilistic parameter. The baseline case is defined as (mean initial crack length)/(pipe circumferential length) = 0.1066.

BWR1 $\Rightarrow$ f_l = exponential, $\mu_l = 0.1066 \cdot (2 \cdot \pi \cdot r_i) = 0.1066 \cdot (2 \cdot \pi \cdot 49) = 32.82$ mm

BWR2 $\Rightarrow$ f_l = exponential, $\mu_l = 0.1066 \cdot (2 \cdot \pi \cdot r_i) = 0.1066 \cdot (2 \cdot \pi \cdot 136.925) = 91.71$ mm

PWR3 $\Rightarrow$ f_l = exponential, $\mu_l = 0.1066 \cdot (2 \cdot \pi \cdot r_i) = 0.1066 \cdot (2 \cdot \pi \cdot 370.9) = 248.42$ mm

1.4 Defect density (C_a^{density}).

The defect density (crack existence/initiations frequency per year and per weld or per weld side) is considered as a deterministic parameter given per year and per weld side.

BWR1 $\Rightarrow$ $C_a^{\text{density}} = 2.687 \cdot 10^{-4}$

BWR2 $\Rightarrow$ $C_a^{\text{density}} = 2.687 \cdot 10^{-4}$

PWR3 $\Rightarrow$ $C_a^{\text{density}} = 2.687 \cdot 10^{-4}$

2. LOADING

2.1 Internal pressure, temperature (p, T).

The internal pressure and operating temperature are deterministic parameters.

BWR1 $\Rightarrow$ p = 7.0 MPa, $T = 286^\circ$C

BWR2 $\Rightarrow$ p = 7.0 MPa, $T = 286^\circ$C

PWR3 $\Rightarrow$ p = 15.41 MPa, $T = 323^\circ$C

2.2 Applied membrane stress (P_m).

The applied membrane stress is a deterministic parameter.

BWR1 $\Rightarrow$ $P_m = 20.0$ MPa

BWR2 $\Rightarrow$ $P_m = 19.2$ MPa

PWR3 $\Rightarrow$ $P_m = 40.4$ MPa

2.3 Applied primary global bending load / stress (P_b).

The applied global bending load is a deterministic parameter.

BWR1 $\Rightarrow$ $P_b = 11.0$ MPa

BWR2 $\Rightarrow$ $P_b = 18.6$ MPa

PWR3 $\Rightarrow$ $P_b = 51.1$ MPa

Comment: In the case of PWR3, the applied stress is taken as $P_b + P_e$*. This is due to the background data, which only gives the sum of these stresses. To be conservative, the assumption in the analysis is to consider this sum to be a primary stress only.*

2.4 Applied "secondary" global bending load / stress (P_e).

The applied "secondary" global bending load (thermal expansion load) is a deterministic parameter.

BWR1 $\Rightarrow$ $P_e = 18.0$ MPa

BWR2 $\Rightarrow$ $P_e = 0.0$ MPa

PWR3 $\Rightarrow$ $P_e = 0.0$ MPa

Comment: In the case of PWR3, the applied stress is included in the primary global bending load.

2.5 Residual stresses ($\sigma_{residual}$).

The residual stresses are considered as a deterministic parameter. A linear distribution is assumed.

BWR1 $\Rightarrow$ $\sigma_{residual} = \pm 233.0$ MPa

BWR2 $\Rightarrow$ $\sigma_{residual} = \pm 50.0$ MPa

PWR3 $\Rightarrow$ $\sigma_{residual} = \pm 100.0$ MPa

Comment: In the case of PWR3, the originally recommended weld residual stress distribution is simplified to be a linear distribution through the thickness of the pipe, although the pipe is very thick. .

2.6 Years in operation (t_{oper}).

The number of years in operation is a deterministic parameter.

$t_{oper} = 60$ years (8000 h/year)

2.7 Design limiting event / stress (σ_{DLE}).

The design limiting event / stress is a deterministic parameter. A design limiting event is not included in the baseline cases.

$\sigma_{DLE} = 0$ MPa

3. MATERIAL DATA

3.1 Yield stress (σ_Y, f_{σ_Y}, μ_{σ_Y}, σ_{σ_Y}).

The yield stress should be a deterministic (Inspecta, VTT) or a probabilistic (JRC) parameter (dependent of the different assumptions in the software). Inspecta and VTT should use the mean values (μ_{σ_Y}).

BWR1 $\Rightarrow$ f_{σ_Y} = normal, $\mu_{\sigma_Y} = 150$ MPa , $\sigma_{\sigma_Y} = 15$ MPa

BWR2 $\Rightarrow$ f_{σ_Y} = normal, $\mu_{\sigma_Y} = 125$ MPa , $\sigma_{\sigma_Y} = 12.5$ MPa

PWR3 $\Rightarrow$ f_{σ_Y} = normal, $\mu_{\sigma_Y} = 150$ MPa , $\sigma_{\sigma_Y} = 15$ MPa

3.2 Ultimate tensile stress (σ_U, f_{σ_U}, μ_{σ_U}, σ_{σ_U}).

The ultimate tensile stress should be a deterministic (Inspecta, VTT) or a probabilistic (JRC) parameter (dependent of the different assumptions in the software). Inspecta and VTT should use the mean values (μ_{σ_U}).

BWR1 $\Rightarrow$ f_{σ_U} = normal, $\mu_{\sigma_U} = 450$ MPa , $\sigma_{\sigma_U} = 30$ MPa

BWR2 $\Rightarrow$ f_{σ_U} = normal, $\mu_{\sigma_U} = 383$ MPa , $\sigma_{\sigma_U} = 30$ MPa

PWR3 $\Rightarrow$ f_{σ_U} = normal, $\mu_{\sigma_U} = 450$ MPa , $\sigma_{\sigma_U} = 30$ MPa

3.3 Fracture toughness (K_{Jc}, $f_{K_{Jc}}$, $\mu_{K_{Jc}}$, $\sigma_{K_{Jc}}$).

The fracture toughness should be a deterministic (Inspecta) or a probabilistic (JRC) parameter (dependent of the different assumptions in the software). The parameter is not used in the VTT model. Inspecta should use the mean values ($\mu_{K_{Jc}}$).

BWR1 $\Rightarrow$ $f_{K_{Jc}}$ = normal, $\mu_{K_{Jc}} = 182\ \text{MPa}\sqrt{\text{m}}$, $\sigma_{K_{Jc}} = 14\ \text{MPa}\sqrt{\text{m}}$

BWR2 $\Rightarrow$ $f_{K_{Jc}}$ = normal, $\mu_{K_{Jc}} = 182\ \text{MPa}\sqrt{\text{m}}$, $\sigma_{K_{Jc}} = 14\ \text{MPa}\sqrt{\text{m}}$

PWR3 $\Rightarrow$ $f_{K_{Jc}}$ = normal, $\mu_{K_{Jc}} = 182\ \text{MPa}\sqrt{\text{m}}$, $\sigma_{K_{Jc}} = 14\ \text{MPa}\sqrt{\text{m}}$

Comment: The fracture toughness is not included in the VTT model.

3.4 Parameters in SCC growth law (C, n).

The parameters in the SCC growth law should be deterministic parameters. For the cases BWR1 and PWR3, Swedish BWR-data is used. For the case BWR2, data from VTT is used with a plateau at $K_I = 55.53\ \text{MPa}\sqrt{\text{m}}$.

BWR1 $\Rightarrow$ $K_I < 55.53\ \text{MPa}\sqrt{\text{m}}$ $\Rightarrow$ $C = 1.46 \cdot 10^{-12}$ mm/s , $n = 3$

$K_I \geq 55.53\ \text{MPa}\sqrt{\text{m}}$ $\Rightarrow$ $da/dt = 2.5 \cdot 10^{-7}$ mm/s

BWR2 $\Rightarrow$ $K_I < 55.53\ \text{MPa}\sqrt{\text{m}}$ $\Rightarrow$ $C = 4.500 \cdot 10^{-12}$ mm/s , $n = 3$

$K_I \geq 55.53\ \text{MPa}\sqrt{\text{m}}$ $\Rightarrow$ $da/dt = 7.705 \cdot 10^{-7}$ mm/s

PWR3 $\Rightarrow$ $K_I < 55.53\ \text{MPa}\sqrt{\text{m}}$ $\Rightarrow$ $C = 1.46 \cdot 10^{-12}$ mm/s , $n = 3$

$K_I \geq 55.53\ \text{MPa}\sqrt{\text{m}}$ $\Rightarrow$ $da/dt = 2.5 \cdot 10^{-7}$ mm/s

3.5 Young's modulus (E).

The Young's modulus is a deterministic parameter.

BWR1 ⇒ $E = 180$ GPa

BWR2 ⇒ $E = 176$ GPa

PWR3 ⇒ $E = 180$ GPa

3.6 Poisson's ratio (ν).

The Poisson's ratio is a deterministic parameter.

BWR1 ⇒ $\nu = 0.3$

BWR2 ⇒ $\nu = 0.3$

PWR3 ⇒ $\nu = 0.3$

VTT RESULTS

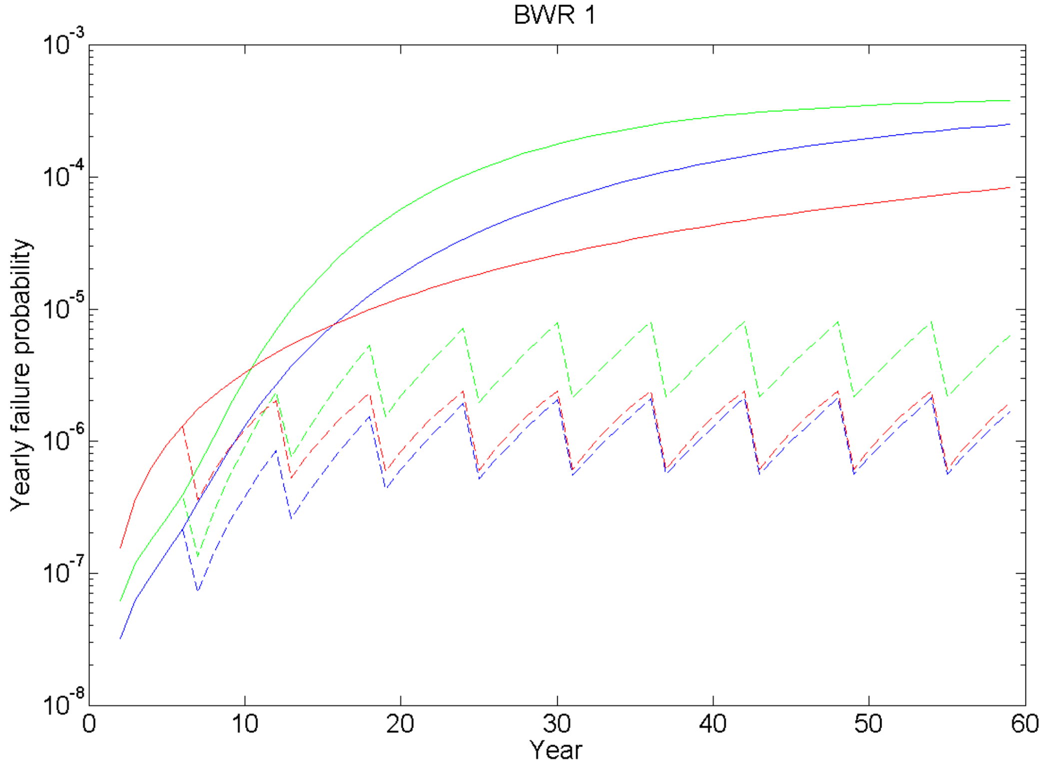

Figure A1 **Sensitivity to crack depth distribution for case BWR1. Green = 50% crack depth distribution, Blue = baseline, Red = 200% crack depth distribution. (VTT)**

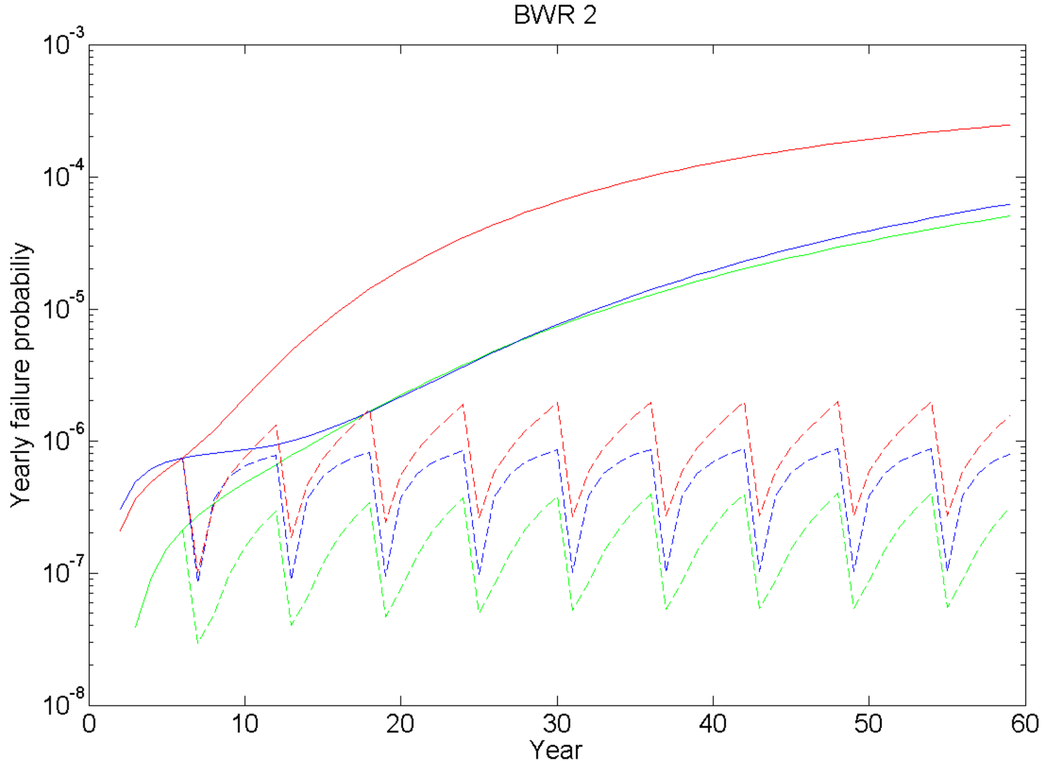

Figure A2 **Sensitivity to crack depth distribution for case BWR2. Green = 50% crack depth distribution, Blue = baseline, Red = 200% crack depth distribution. (VTT)**

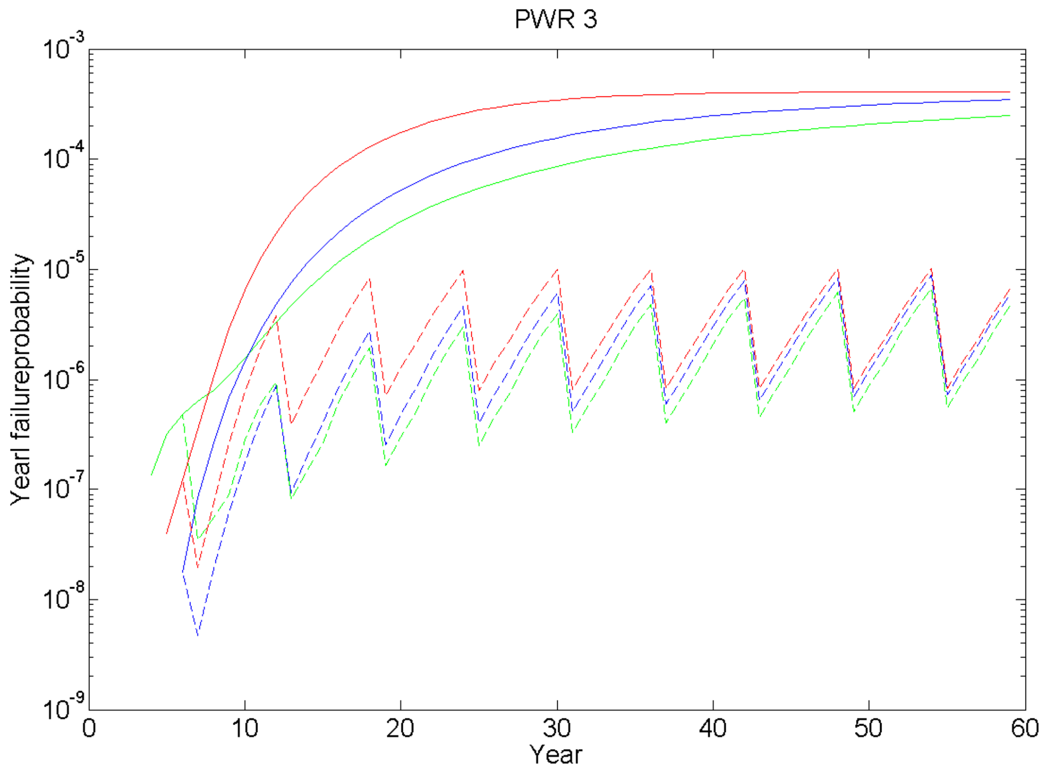

Figure A3 **Sensitivity to crack depth distribution for case PWR3. Green = 50% crack depth distribution, Blue = baseline, Red = 200% crack depth distribution. (VTT)**

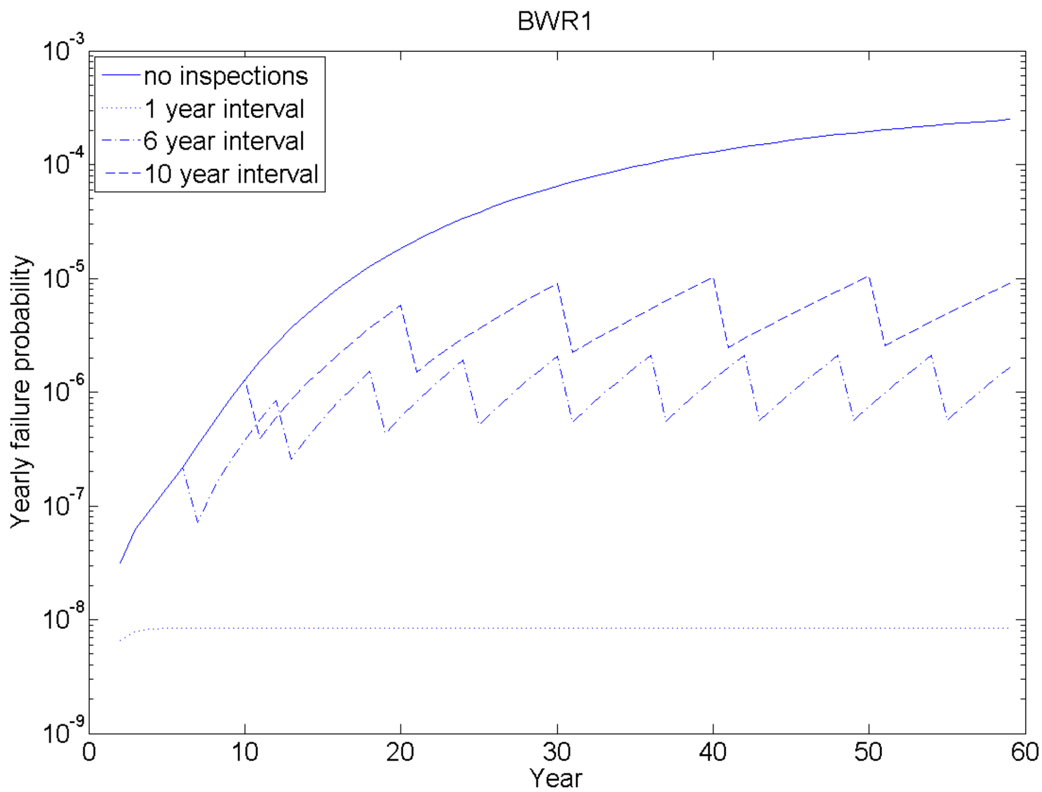

Figure A4 **Sensitivity of yearly leakage probability to inspection intervals for case BWR1. (VTT)**

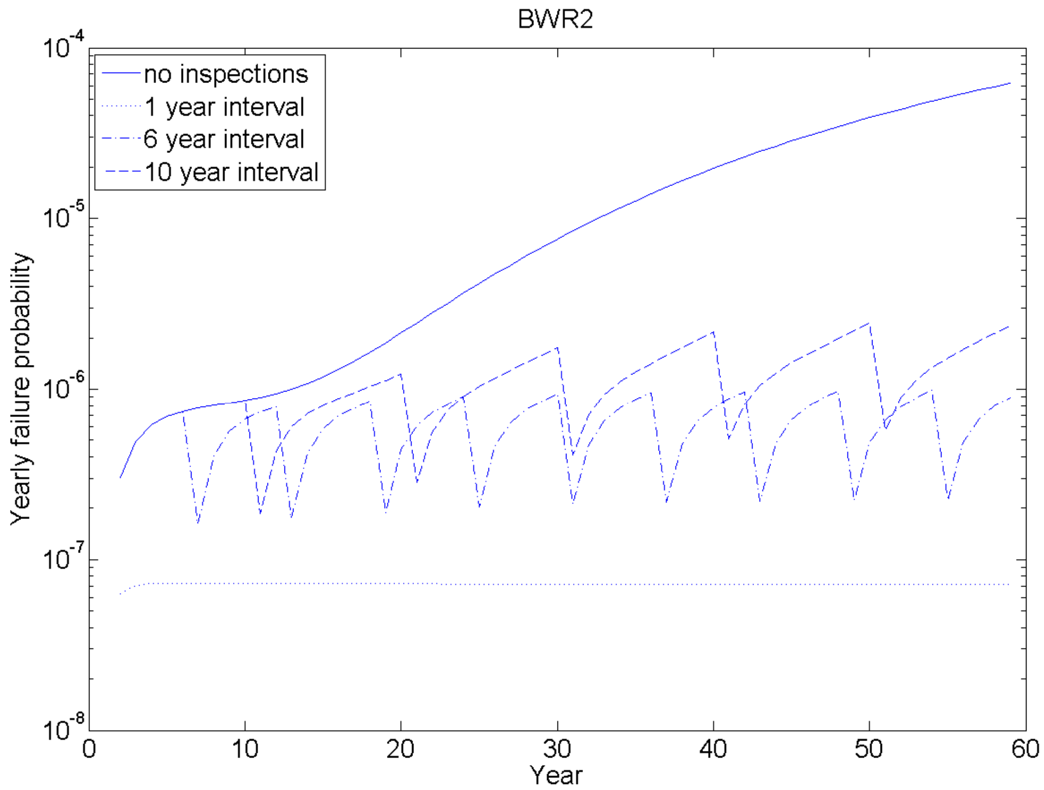

Figure A5 **Sensitivity of yearly leakage probability to inspection intervals for case BWR2. (VTT)**

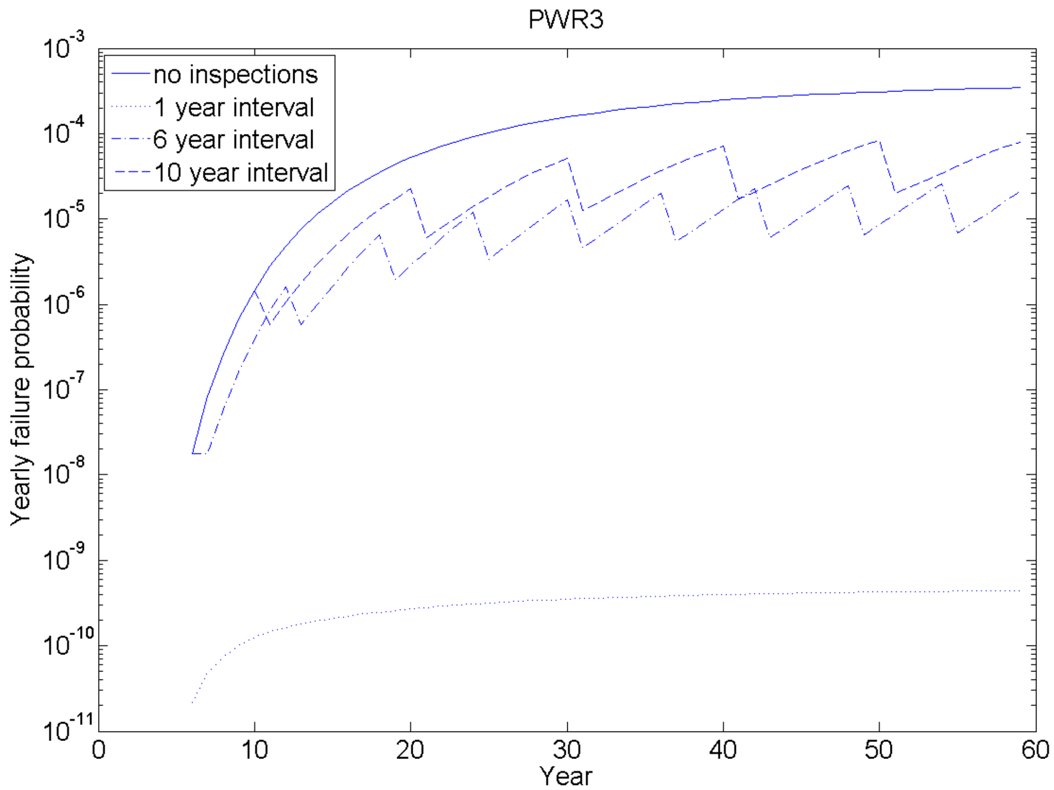

Figure A6 **Sensitivity of yearly leakage probability to inspection intervals for case PWR3. (VTT)**

Table A1 Analysis results of VTT method sensitivity to crack depth distribution

	Depth distr.	POD	Last 6 years average	Risk reduction RRF	R	Percentage of baseline
BWR1	**50 %**	SKI POD	4,67E-06	79	99 %	383 %
		No inspections	3,70E-04			158 %
	100 %	SKI POD	1,22E-06	192	99 %	100 %
		No inspections	2,34E-04			100 %
	200 %	SKI POD	1,40E-06	55	98 %	115 %
		No inspections	7,69E-05			33 %
BWR2	**50 %**	SKI POD	2,06E-07	219	100 %	36 %
		No inspections	4,51E-05			82 %
	100 %	SKI POD	5,70E-07	97	99 %	100 %
		No inspections	5,52E-05			100 %
	200 %	SKI POD	1,07E-06	216	100 %	188 %
		No inspections	2,31E-04			418 %
PWR3	**50 %**	SKI POD	2,86E-06	83	99 %	77 %
		No inspections	2,36E-04			70 %
	100 %	SKI POD	3,73E-06	90	99 %	100 %
		No inspections	3,36E-04			100 %
	200 %	SKI POD	4,21E-06	96	99 %	113 %
		No inspections	4,05E-04			121 %

Table A2 Analysis results of VTT method sensitivity to inspection intervals

Case	Inspection interval	Last 6 years average	RRF	R	Percentage of baseline
BWR1	6- years	1,22E-06	192	99 %	100 %
	1- year	8,49E-09	27592	100 %	1 %
	10- year	6,39E-06	37	97 %	522 %
	No inspections	2,34E-04			
BWR2	6- years	5,70E-07	97	99 %	100 %
	1- year	3,48E-08	1585	100 %	6 %
	10- year	1,37E-06	40	98 %	240 %
	No inspections	5,52E-05			
PWR3	6- years	3,73E-06	90	99 %	100 %
	1- year	1,12E-12	300357143	100 %	0 %
	10- year	2,45E-05	14	93 %	657 %
	No inspections	3,36E-04			

INSPECTA NURBIT RESULTS

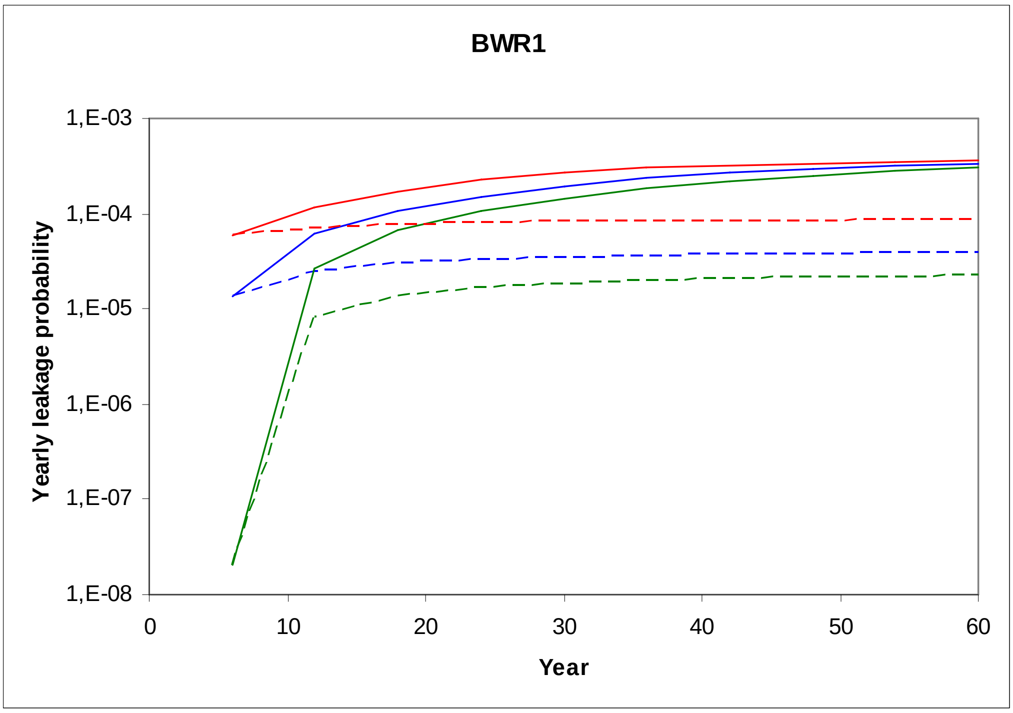

Figure A7 **NURBIT results showing the sensitivity to crack depth distribution for case BWR1. Green = 50% crack depth distribution, Blue = baseline, Red = 200% crack depth distribution. Solid line is without inspection and hatched line is for the SKI POD and 6-years interval.**

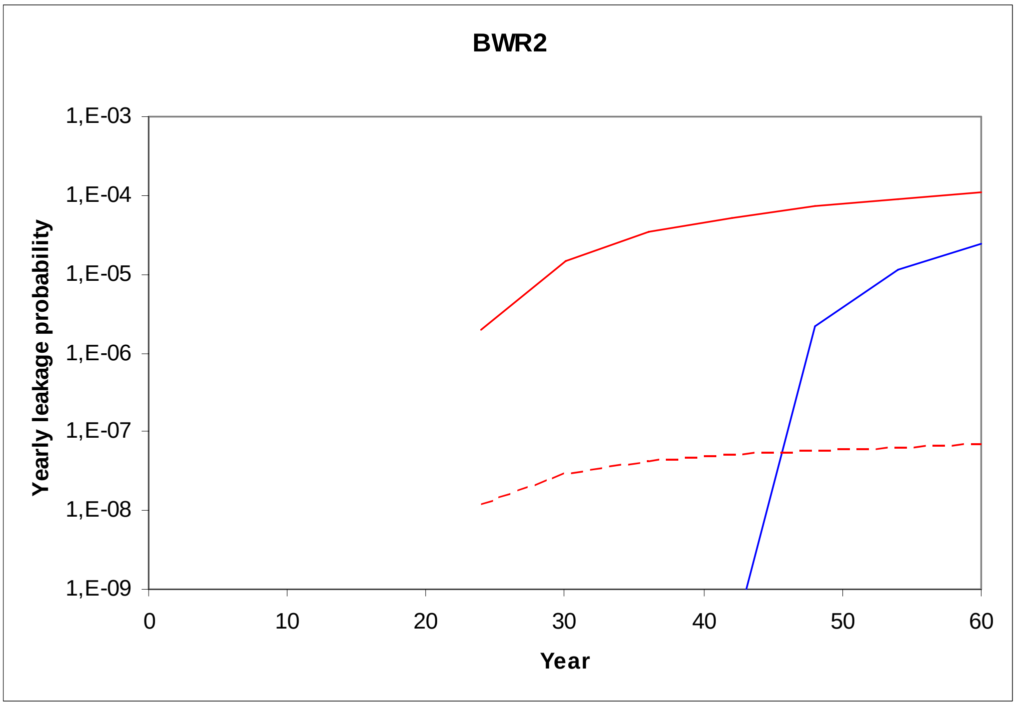

Figure A8 **Sensitivity to crack depth distribution for case BWR2. Blue = baseline, Red = 200% crack depth distribution. For 50 % crack depth distribution no crack growth could be calculated. (NURBIT)**

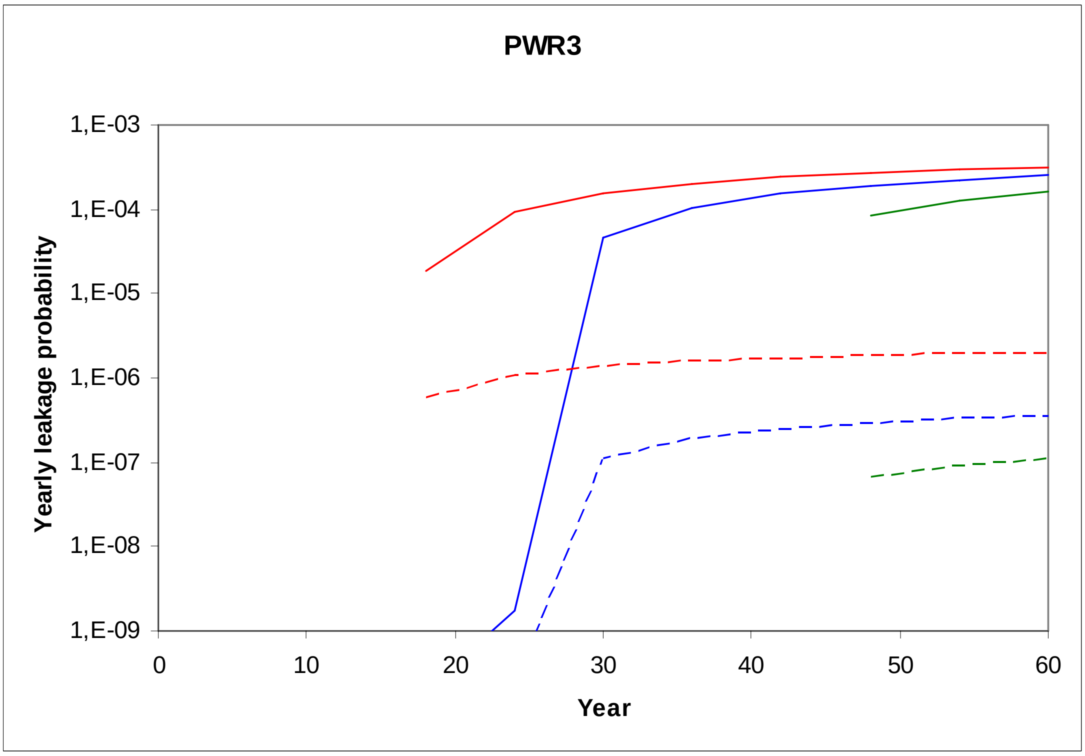

Figure A9 **Sensitivity to crack depth distribution for case BWR2. Green = 50% crack depth distribution, Blue = baseline, Red = 200% crack depth distribution. (NURBIT)**

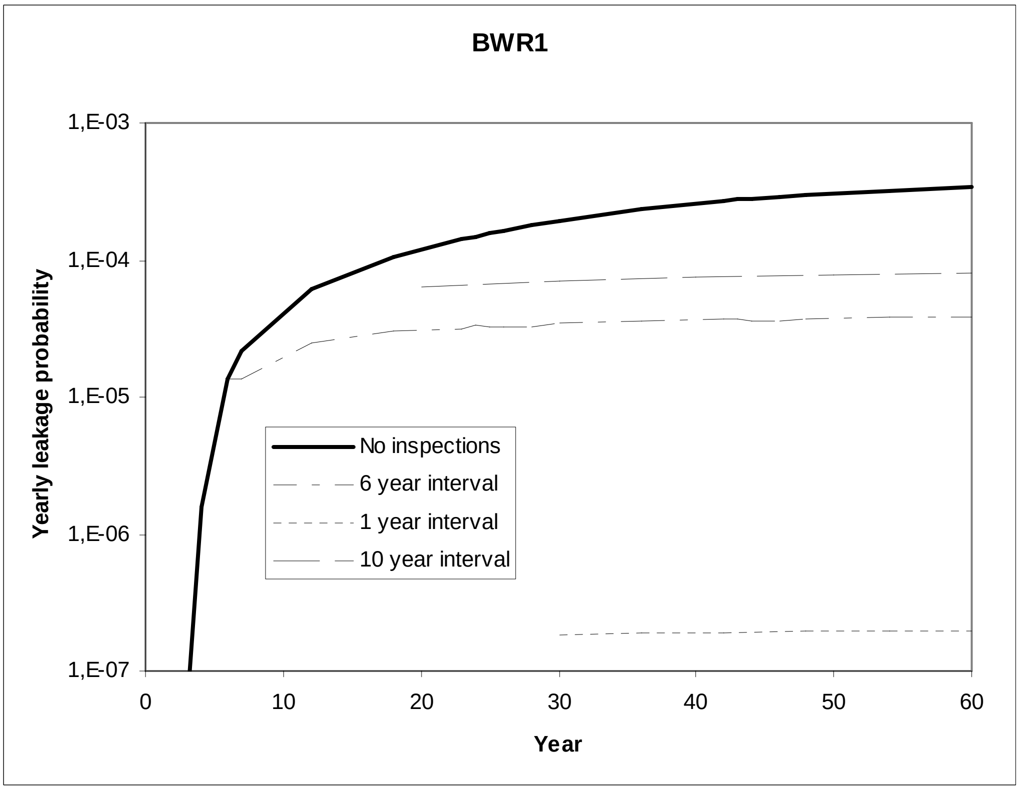

Figure A10 **Sensitivity of yearly leakage probability to inspection intervals for case BWR1. (NURBIT)**

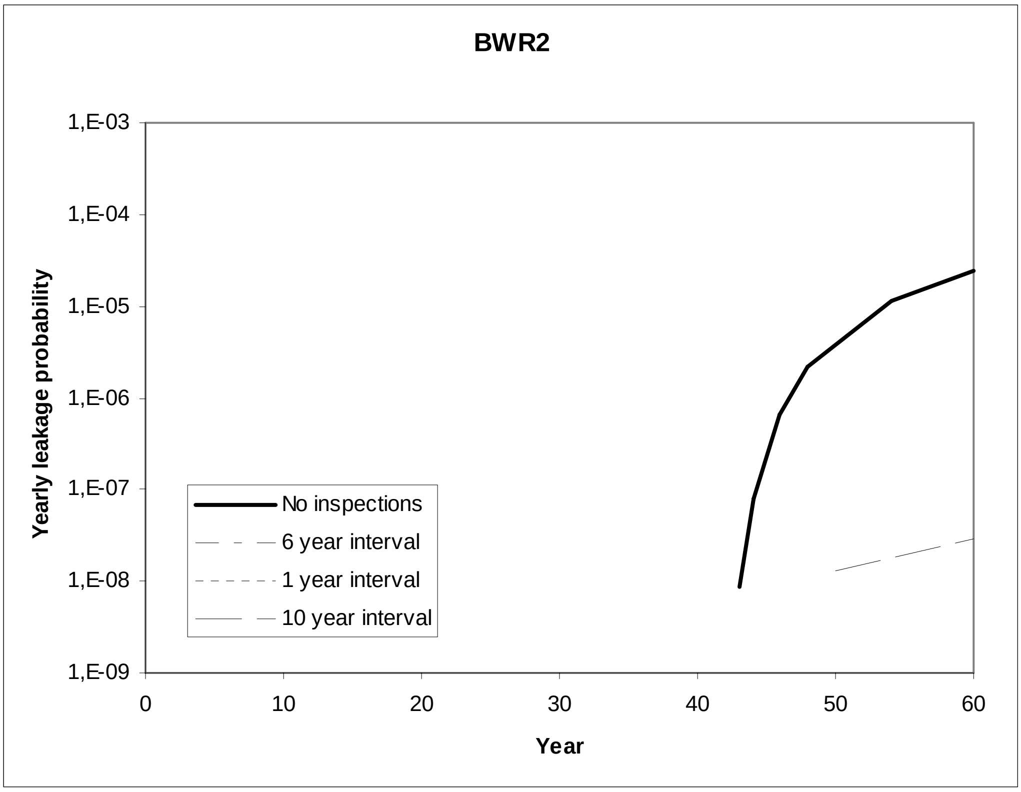

Figure A11 Sensitivity of yearly leakage probability to inspection intervals for case BWR2. (NURBIT)

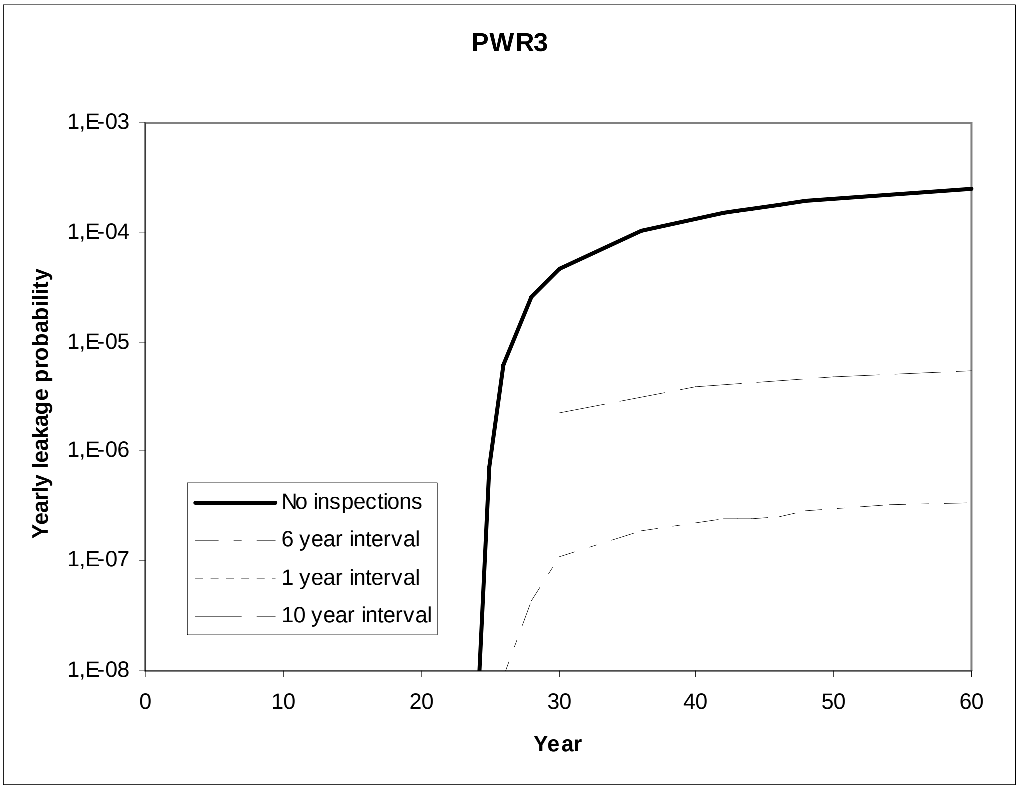

Figure A12 Sensitivity of yearly leakage probability to inspection intervals for case PWR3. (NURBIT)

Table A3 Analysis results of INSPECTA NURBIT method sensitivity to crack depth distribution

	Depth distr.	POD	Last 6 years average (*)	Risk reduction RRF	R	Percentage of baseline
BWR1	**50 %**	SKI POD	2,23E-05	14	93 %	58 %
		No inspections	3,05E-04			90 %
	100 %	SKI POD	3,86E-05	9	89 %	
		No inspections	3,38E-04			
	200 %	SKI POD	8,53E-05	4	76 %	222 %
		No inspections	3,60E-04			107 %
BWR2	**50 %**	SKI POD	0			0
		No inspections	0			0
	100 %	SKI POD	2,45E-10	103588	100 %	
		No inspections	2,43E-05			
	200 %	SKI POD	6,65E-08	1637	100 %	28390 %
		No inspections	1,09E-04			449 %
PWR3	**50 %**	SKI POD	1,07E-07	1489	100 %	42 %
		No inspections	1,60E-04			65 %
	100 %	SKI POD	3,48E-07	979	100 %	
		No inspections	2,50E-04			
	200 %	SKI POD	1,94E-06	164	99 %	770 %
		No inspections	3,20E-04			129 %

(*) Note: Last year results used except for base case.

Table A4 Analysis results of INSPECTA NURBIT method sensitivity to inspection intervals

Case	Inspection interval	Last 6 years average (*)	RRF	R	Percentage of baseline
BWR1	6- years	3,86E-05	9	89 %	100 %
	1- year	1,96E-07	1724	100 %	1 %
	10- year	8,06E-05	4	76 %	209 %
	No inspections	3,38E-04			
BWR2	6- years	2,45E-10	103588	100 %	100 %
	1- year	0	infinite	100 %	0 %
	10- year	2,87E-08	846	100 %	12247 %
	No inspections	2,43E-05			
PWR3	6- years	3,48E-07	979	100 %	100 %
	1- year	0	infinite	100 %	0 %
	10- year	5,52E-06	45	98 %	2187 %
	No inspections	2,50E-04			

(*) Note: Last year results used except for base case.

JRC RESULTS

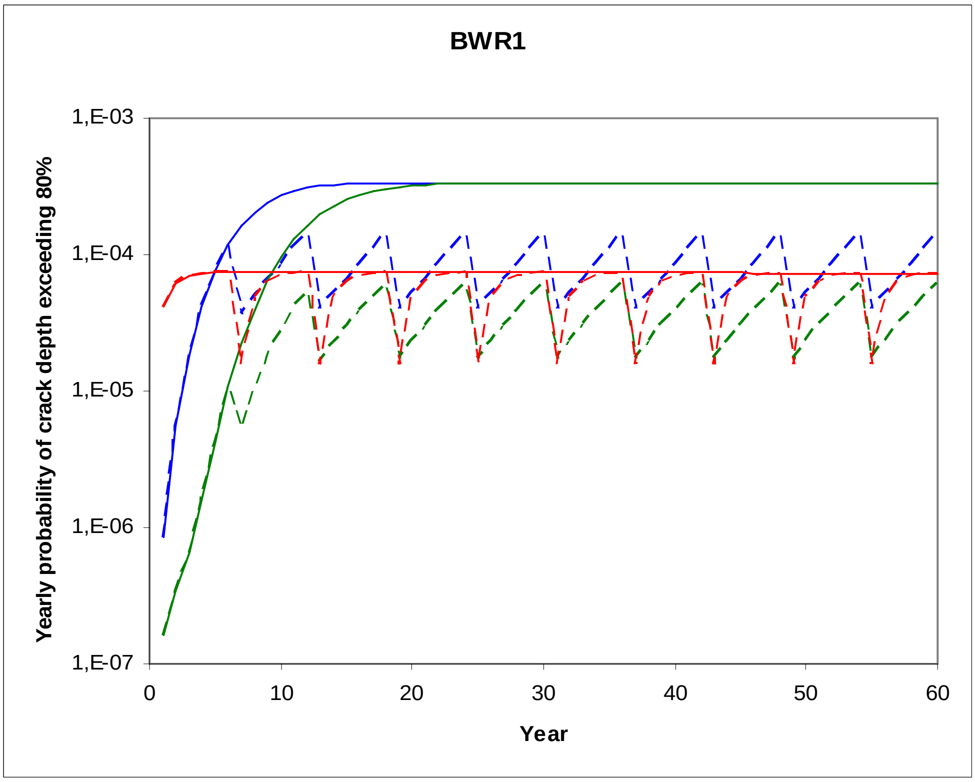

Figure A13 **Sensitivity to crack depth distribution for case BWR1. Green = 50% crack depth distribution, Blue = baseline, Red = 200% crack depth distribution. (JRC)**

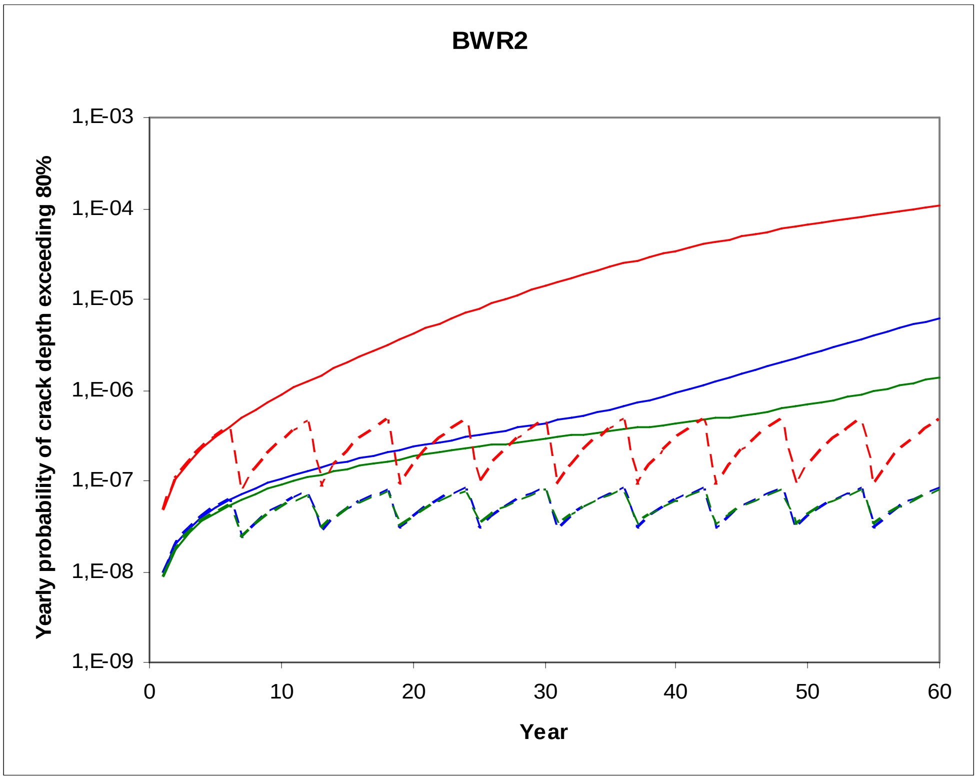

Figure A14 **Sensitivity to crack depth distribution for case BWR2. Green = 50% crack depth distribution, Blue = baseline, Red = 200% crack depth distribution. (JRC)**

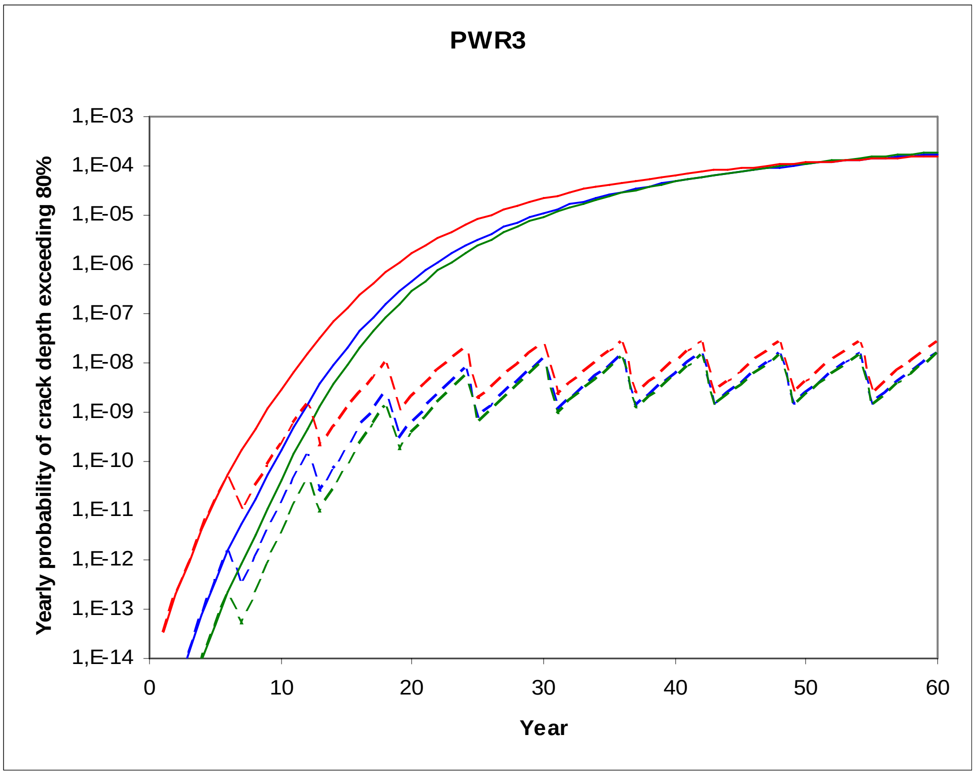

Figure A15 **Sensitivity to crack depth distribution for case BWR2. Green = 50% crack depth distribution, Blue = baseline, Red = 200% crack depth distribution. (JRC)**

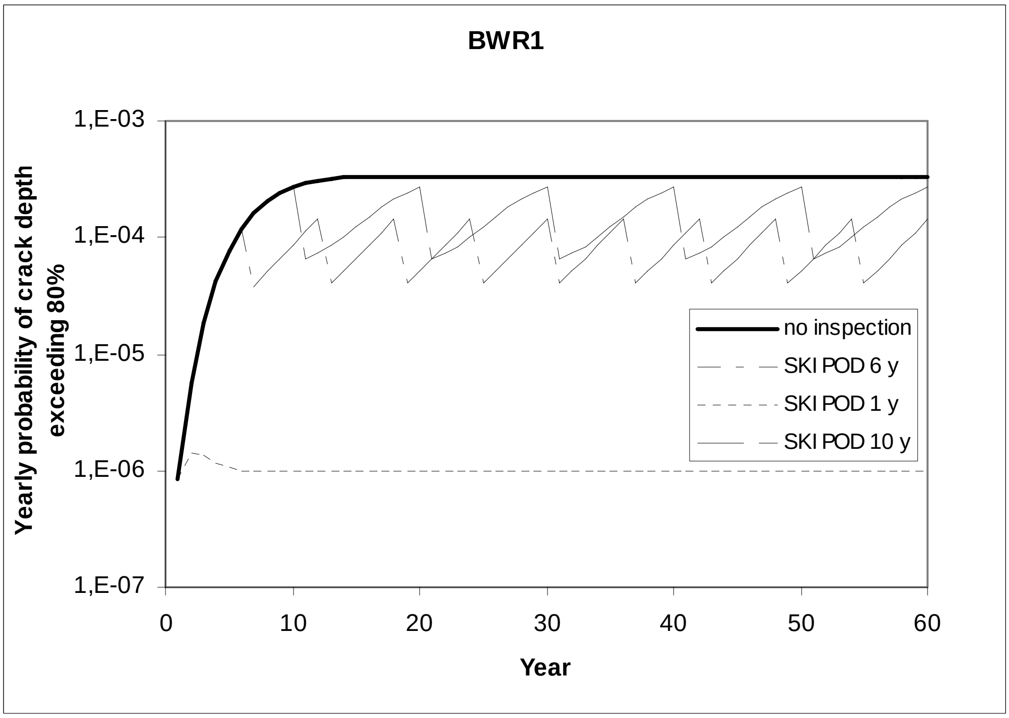

Figure A16 **Sensitivity of yearly leakage probability to inspection intervals for case BWR1. (JRC)**

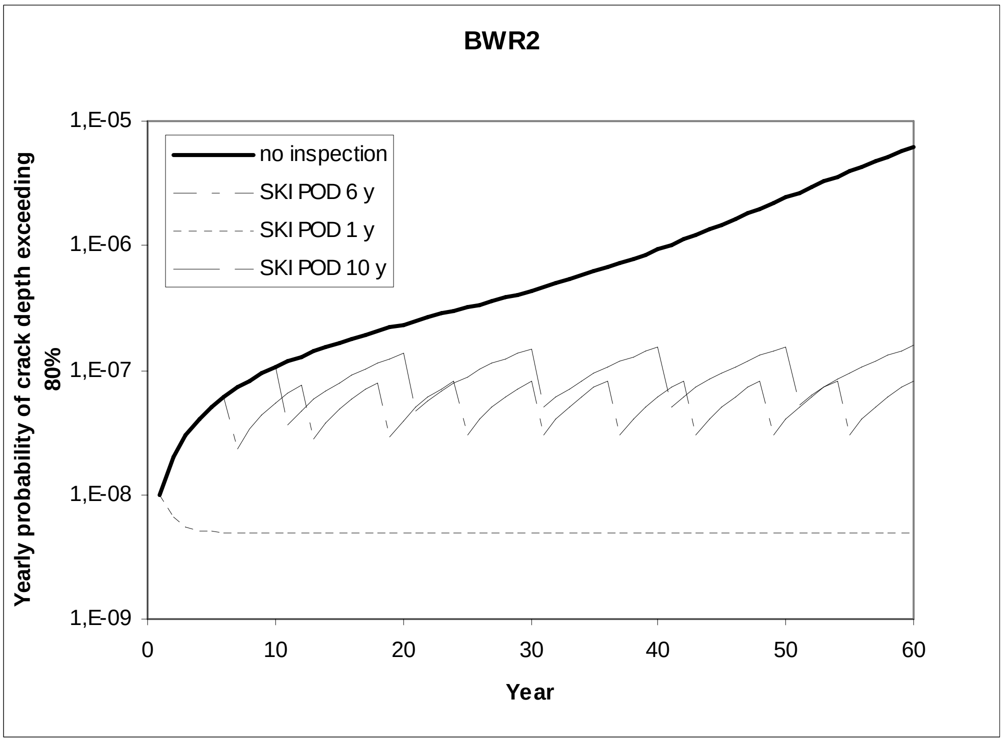

Figure A17 **Sensitivity of yearly leakage probability to inspection intervals for case BWR2. (JRC)**

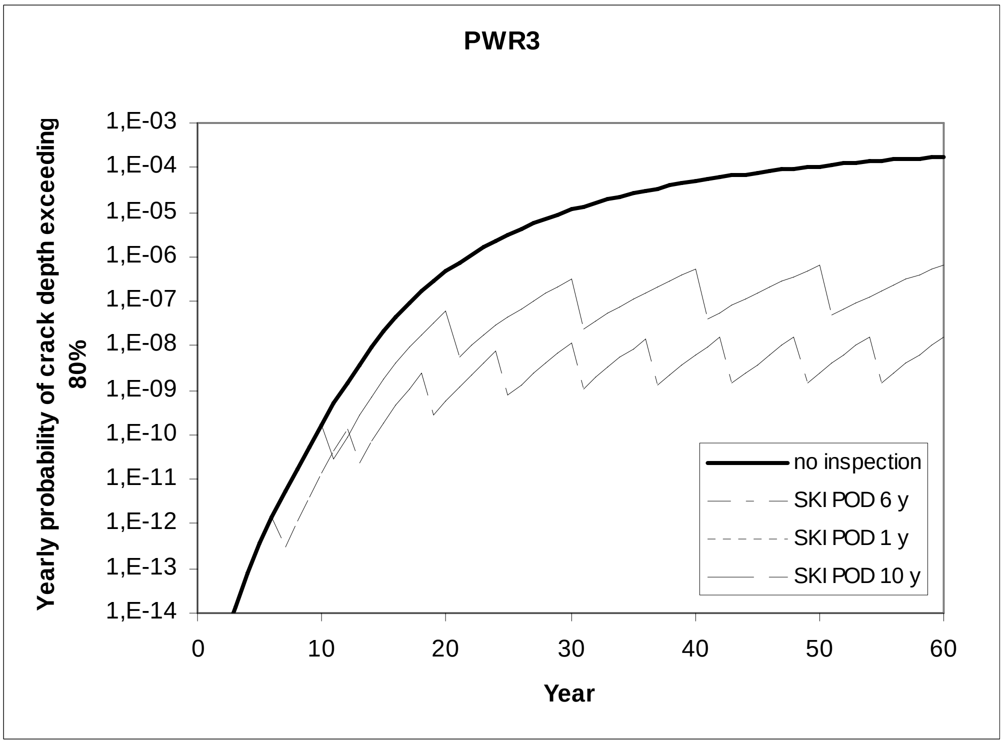

Figure A18 **Sensitivity of yearly leakage probability to inspection intervals for case PWR3. (JRC)**

Table A5 Analysis results of JRC method sensitivity to crack depth distribution

	Depth distr.	POD	Last 6 years average	Risk reduction RRF	R	Percentage of baseline
BWR1	**50 %**	SKI POD	3,71E-05			45 %
		No inspections	3,32E-04	9	89 %	100 %
	100 %	SKI POD	8,30E-05			
		No inspections	3,31E-04	4	75 %	
	200 %	SKI POD	5,72E-05			69 %
		No inspections	7,33E-05	1	22 %	22 %
BWR2	**50 %**	SKI POD	5,54E-08			98 %
		No inspections	1,16E-06	21	95 %	23 %
	100 %	SKI POD	5,63E-08			
		No inspections	5,03E-06	89	99 %	
	200 %	SKI POD	2,66E-07			473 %
		No inspections	9,59E-05	360	100 %	1906 %
PWR3	**50 %**	SKI POD	6,27E-09			93 %
		No inspections	1,72E-04	27390	100 %	108 %
	100 %	SKI POD	6,75E-09			
		No inspections	1,58E-04	23479	100 %	
	200 %	SKI POD	1,15E-08			171 %
		No inspections	1,49E-04	12903	100 %	94 %

Table A6 Analysis results of JRC method sensitivity to inspection intervals

Case	Inspection interval	Last 6 years average	RRF	R	Percentage of baseline
BWR1	6- years	8,30E-05	4	75 %	100 %
	1- year	9,80E-07	338	100 %	1 %
	10- year	1,96E-04	2	41 %	236 %
	No inspections	3,31E-04			
BWR2	6- years	5,63E-08	89	99 %	100 %
	1- year	4,97E-09	1012	100 %	9 %
	10- year	1,26E-07	40	97 %	224 %
	No inspections	5,03E-06			
PWR3	6- years	6,75E-09	23479	100 %	100 %
	1- year	0,00E+00	infinite	100 %	0 %
	10- year	3,83E-07	414	100 %	5675 %
	No inspections	1,58E-04			

Title	Studies on the effect of flaw detection probability assumptions on risk reduction at inspection
Author(s)	Kaisa Simola(1), Otso Cronvall(1), Ilkka Männistö(1), Jens Gunnars (2), Lars Alverlind(2), Peter Dillström(2), Luca Gandossi(3)
Affiliation(s)	(1) VTT Technical Research Centre of Finland, (2) Inspecta Technology, (3) European Commission Joint Research Centre
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Abstract

The aim of the project was to study the effect of POD assumptions on failure probability using structural reliability models. The main interest was to investigate whether it is justifiable to use a simplified POD curve e.g. in risk-informed in-service inspection (RI-ISI) studies. The results of the study indicate that the use of a simplified POD curve could be justifiable in RI-ISI applications.

Another aim was to compare various structural reliability calculation approaches for a set of cases. Through benchmarking one can identify differences and similarities between modelling approaches, and provide added confidence on models and identify development needs. Comparing the leakage probabilities calculated by different approaches at the end of plant lifetime (60 years) shows that the results are very similar when inspections are not accounted for. However, when inspections are taken into account the predicted order of magnitude differs. Further studies would be needed to investigate the reasons for the differences. Development needs and plans for the benchmarked structural reliability models are discussed.

Key words: Structural reliability, in-service inspections, NDE, probability of detection

Available on request from the NKS Secretariat, P.O.Box 49, DK-4000 Roskilde, Denmark.
Phone (+45) 4677 4045, fax (+45) 4677 4046, e-mail nks@nks.org, www.nks.org