Strål
säkerhets
myndigheten
Swedish Radiation Safety Authority

Author: Andrey Shipsha

Research

2016:37

PARTRIDGE project:

Review and evaluation of the probabilistic fracture mechanics code PRO-LOCA

Report number: 2016:37 ISSN: 2000-0456
Available at www.stralsakerhetsmyndigheten.se

SSM perspective

Background

SSM and the Swedish nuclear power plant owners have financed Inspecta Technology in Sweden to evaluate the PRO-LOCA code. It is a computer code, developed by Battelle in the USA, in which the leak- and rupture probabilities of piping in nuclear power plants are analysed. The pipe systems may contain the damage mechanisms fatigue and/or stress corrosion cracking. In the report, the results are presented for evaluating PRO-LOCA, version 4.1.9. The report contains a sensitivity study for both PWR PWSCC and BWR fatigue.

Objective

The primary objective has been to make an independent quality check, to detect possible bugs in the code and to suggest improvements. Another objective has been to understand what the key parameters are in this type of probabilistic approach.

Results

1. The PRO-LOCA code is capable to predict the leak or rupture probabilities of nuclear piping systems taking into account the whole sequence of crack initiation of a circumferential crack, subcritical growth until wall penetration following by leakage and further crack growth (if undetected) until possible instability of the through-wall crack (pipe rupture).
2. Performed benchmark analyses and parametric sensitivity studies are presented for two main cases, a PWR pipe subject to PWSCC degradation, and a BWR pipe under fatigue cracking.
3. The main influencing parameters on the predicted probabilities for the PWSCC case are growth rate, weld residual stress, inspection interval, inspection effectiveness and leak rate detection capability.
4. The main influencing parameters on the predicted probabilities for the BWR fatigue case are initial defect size, growth rate, inspection interval, inspection effectiveness and leak rate detection capability.
5. For BWR fatigue, unrealistic results were obtained for variation of ultimate tensile strength. This should be investigated further.
6. Leak rate detection is a powerful way to detect leaks before a pipe break, i.e. the tendency for LBB (Leak Before Break) in the studied cases is quite strong. If a reliable leak detection system is implemented in a pipe system, the only way a break can occur is if the stress state (i.e. system loads and weld residual stresses) are distributed in a way that an initiated circumferential crack will grow almost around the whole circumference before wall penetration. If then eventually a wall penetration occurs, the crack may be immediately unstable and a pipe rupture will occur.

Need for further research

There is a need to further verify the PRO-LOCA code in order to make it useful for other than research purposes. The ultimate objective is that PRO-LOCA can be a validated and verified tool to analyse leak- and rupture probabilities of nuclear power plant piping to assist making sensible decisions if damages are detected.

Project information

Contact person SSM: Björn Brickstad
Reference: SSM2010-3299 and SSM2014-977

Strål
säkerhets
myndigheten

Swedish Radiation Safety Authority

Author: Andrey Shipsha

Inspecta Technology AB, Stockholm

2016:37

PARTRIDGE project:

Review and evaluation of the probabilistic fracture mechanics code PRO-LOCA

Date: November 2016
Report number: 2016:37 **ISSN:** 2000-0456
Available at www.stralsakerhetsmyndigheten.se

PARTRIDGE project: Review and evaluation of the probabilistic fracture mechanics code PRO-LOCA

Summary

This report summarizes the activities of Inspecta Technology AB in following the technical basis development and evaluating the PRO-LOCA code under PARTRIDGE program. PARTRIDGE project has been conducted by the Battelle Memorial Institute (Columbus, Ohio, USA) aiming to take a further step in development of the probabilistic code PRO-LOCA.

The PRO-LOCA code is capable to predict the leak or rupture probabilities of nuclear piping systems taking into account the whole sequence of crack initiation, subcritical growth until wall penetration and leakage and instability of the through-wall crack (pipe rupture). The outcome of the PRO-LOCA code are a sequence of probabilities, which represent the probability of a surface crack developing, a through-wall crack developing and six different sizes of crack opening areas corresponding to different leak flow rates or LOCA categories.

This report presents the current technical basis of the PRO-LOCA code, Version 4.1.9, summarising the main improvements and changes introduced into PRO-LOCA as a result of PARTRIDGE program. It also gives a short introduction to practical aspects of using the PRO-LOCA code, Version 4.1.9 for probabilistic analyses.

Performed benchmark analyses and parametric sensitivity studies are presented for two main cases, a PWR pipe subject to PWSCC degradation, and a BWR pipe under fatigue cracking. The different aspects of PRO-LOCA capabilities and underlying models are assessed. The adequacy of the observed trends is discussed and compared with previous studies.

The report finally presents a discussion about relevance and importance of using PRO-LOCA and other PFM codes for the Swedish nuclear industry and regulatory body. First, an overview of the existing regulatory requirements and current application of probabilistic methods is presented. It is followed by the discussion of new requirements that may be introduced in regulatory documents and new challenges that may arise under long term operation (LTO) of aged reactors.

Acronyms

The following acronyms (sorted alphabetically) are used in this report:

BWR	Boiling Water Reactor
CFP	Crack Face Pressure
CGR	Crack Growth Rate
COA	Crack Opening Area
DEGB	Double ended “guillotine” break
DM	Dissimilar Metal
DMW	Dissimilar Metal Weld
EPRI	Electric Power Research Institute
FEA	Finite Element Analysis
GDC	General Design Criteria
HAZ	Heat Affected Zone
IGSCC	Intergranular Stress Corrosion Cracking
ISI	In-Service Inspection
LBB	Leak Before Break
LOCA	Loss Of Coolant Accident
MERIT	Maximizing Enhancements in Risk-Informed Technology
NURBIM	Nuclear Risk-Based Inspection Methodology for passive components
PARTRIDGE	Probabilistic Analysis as a Regulatory Tool for Risk-Informed Decision Guidance
U.S.NRC	United States Nuclear Regulatory Commission
PFM	Probabilistic Fracture Mechanics
POD	Probability Of Detection
PWR	Pressurized Water Reactor
PWSCC	Primary Water Stress Corrosion Cracking
QA	Quality Assurance
RI-ISI	Risk-Informed In-Service Inspection
RPV	Reactor Pressure Vessel
SC	Surface Crack
SCC	Stress Corrosion Cracking
SQUIRT	Seepage Quantification of Upsets In Reactor Tubes
SRP	Standard Review Plan
SSE	Safe Shutdown Earthquake
SSM	Swedish Radiation Safety Authority
TAG	Technical Advisory Group
TWC	Through-Wall Crack
UWFM	Universal Weight Function method
WRS	Weld Residual Stress
xLPR	Extremely Low Probability of Rupture

Contents

1 Project information

1.1 Roles and responsibilities

PARTRIDGE project has been conducted by the Battelle Memorial Institute (Columbus, Ohio, USA) aiming to further develop the probabilistic code PRO-LOCA.

The project has been financed by an international consortium, including the Swedish Radiation Safety Authority (SSM).

Inspecta Technology AB has been commissioned by the Swedish Nuclear Utility Analysis Group (BG) and by the SSM (at the final stage of the project) for:

- Following the PRO-LOCA development;
- Reviewing the technical basis for different modules (e.g. crack initiation, growth, etc.) included in the code;
- Performing benchmark and sensitivity analyses in order to assess general behaviour of the code and adequacy of demonstrated trends;
- Evaluating the project importance and relevance for Swedish nuclear industry and regulatory work.

The project leaders from customer organizations for the Inspecta assignment in PARTRIDGE project are:

Mr. Stefan Olsson (OKG AB)
Dr. Johan Lundvall (Forsmark Kraftgrupp AB)
Mr. Jan Lagerström (Ringhals AB)
Dr. Björn Brickstad (SSM)

1.2 Acknowledgements

PARTRIDGE project has been running since 2011 and involved several Inspecta staff members, namely Iradj Sattari-Far (resigned 2013), Carl von Feilitzen, Weilin Zang (currently at OKG AB), Peter Dillström and Jens Gunnars. All these persons are greatly acknowledged for their contributions in earlier stages of the project.

2 Introduction

This introductory section provides the short background on motivation and chronology of the development of the probabilistic fracture mechanics (PFM) code PRO-LOCA. This section also defines the objective and scope of this study and describes the layout structure of the report.

2.1 Motivation for PRO-LOCA development

According to the U.S. Code of Federal Regulations (10 CFR 50.46), Appendix K to Part 50, an emergency core cooling system (ECCS) in a nuclear power plant is currently required to ensure that the system can successfully mitigate postulated design basis loss-of-coolant-accidents (LOCA) considering an instantaneous break with a flow rate equivalent to a double-ended "guillotine" break (DEGB) of the largest primary piping system.

Similar requirements can also be found in regulatory codes of other countries. Thus, the Swedish regulation SSMFS 2008:17, § 3 stipulates that a nuclear power reactor shall be designed ensuring the maintained safety functions, including the emergency core cooling, during all event classes ≥H4. Additionally, the design shall take into account the events ≥H5 so that according to § 7 a reactor core can be cooled for all types and sizes of LOCA that can result from breaks of piping connected to the RPV.

A DEGB of the largest primary system piping is widely recognized as an extremely unlikely event and its consideration in nuclear plant design and operation requires significant resources and costs that might not be comparable with the associated risk. Relaxing the deterministic DEGB event requirement could allow for focusing resources on more risk-significant events and potentially improving plant safety.

The U.S. Nuclear Regulatory Commission (NRC) has initiated a work to establish a risk-informed approach to the design-basis break size requirements in 10 CFR 50.46. A cornerstone for selecting a risk-informed design basis break size instead of DEGB criterion is an understanding of the leakage and rupture frequencies as a function of piping system break size. An attempt to establish a relationship between the break sizes and break frequency has been undertaken using an expert elicitation process based on service history data and knowledge of plant design, operation and material performance. Results of this elicitation process along with applied methods, used assumptions and identified limitations were reported in NUREG-1829 [1].

Followed by this elicitation study the need for an improved PFM code became evident. The NRC needed a tool for verifying the results from the elicitation effort and for periodic re-evaluation of the established LOCA frequencies to determine if they should be updated based on information and knowledge gained subsequent to the expert elicitation. In 2003, the NRC began the development of a new code called PRO-LOCA. It was envisioned that the PRO-LOCA code will include the improved models (e.g. for crack initiation/growth, leak-rate with crack morphology parameters, etc.) and new degradation mechanisms that have been developed/investigated since the development of some of the earlier PFM codes (e.g. PRAISE).

Development of the PRO-LOCA is also motivated by other potential applications which include: (1) a general purpose PFM code for assisting with leak-before-break (LBB) assessment, (2) a flaw assessment tool helping to evaluate the failure probability of a piping system once a flaw is detected in service, and (3) a tool for prioritization of plant maintenance activities, such as in-service inspections (ISI).

2.2 Chronology of PRO-LOCA development

2.2.1 Early stage (PRO-LOCA 1.0)

The first version of the PRO-LOCA 1.0 code was developed by the Battelle Memorial Institute and the Engineering Mechanics Corporation (EMC^2) under the NRC contract. The PRO-LOCA code was intended to include the latest technology in fracture mechanics since the development of the earlier probabilistic codes. The technical basis of the PRO-LOCA 1.0 code along with the description of implemented features has been presented at the ASME PVP conference in 2006 [2].

Like PRAISE, the first version PRO-LOCA code could address failure mechanisms associated with both pre-existing and service-induced cracks subject to fatigue and IGSCC degradation mechanisms. In addition, primary water stress corrosion cracking (PWSCC) for dissimilar metal welds (DMW) in pressurized water reactors (PWRs) has been included in PRO-LOCA. The PWSCC degradation mechanism has previously not been considered in existing PFM codes but was recognised as a significant issue after several incidents in PWR plants [3].

Also, PRO-LOCA is capable of predicting the probabilities of crack opening areas (COA) and leak rates from LOCAs as well as predicting of critical/unstable crack sizes for all implemented degradation mechanisms (fatigue, IGSCC, PWSCC). The latest deterministic models for crack initiation and growth for all considered degradation mechanisms have also been included in PRO-LOCA. The code provides a possibility to model multiple crack initiation sites and account for crack coalescence which is necessary for modelling the development of the long surface cracks which are thought to be precursor events to the larger COAs. Consideration of weld residual stresses (WRS) has been improved in the PRO-LOCA code by including expressions for the through thickness WRS for a variety of pipe geometries based on detailed finite-element analyses. These solutions were obtained for a number of typical piping geometries for both BWR and PWR plants including DM welds as well as stainless-to-stainless steel welds [2].

Even though the initial version of PRO-LOCA can be seen as a significant leap in PFM analysis technology in comparison with previous codes, a number of issues have been identified for further development. Thus, this initial version of the code (Version 1.0) is based on a model which assumes uniform stress around the pipe circumference and, therefore, does not account for stress gradient due to bending loads. This version of PRO-LOCA is based on the classic Monte Carlo probabilistic method which requires a great number of simulations to assess low probability events. Further development of the code was planned to include adaptive and importance sampling techniques and discrete probability distribution approach. Other planned enhancements to PRO-LOCA will be discussed in detail in the following sections.

Finally, the initial version of PRO-LOCA 1.0 was not suitable to be released to external organizations for testing and verification purposes as the code was lacking proper documentation and detailed user instructions. Development of the documentation was intended to be a part of planned future work on PRO-LOCA.

2.2.2 MERIT program (PRO-LOCA 2.0) and xLPR program (xLPR 1.0)

Further development of the PRO-LOCA code was performed by Battelle and EMC^2 through a three year international cooperative research program entitled Maximizing Enhancements in Risk Informed Technology (MERIT). MERIT program has included participation from Canada (CANDU Energy Inc.), Korea (consortium of interests), Sweden (SSM), UK (Rolls Royce), and the US (NRC and EPRI). Representatives from these countries and organisations have established a Technical Advisory Group (TAG) which was actively participating in testing and benchmarking of the code and providing feedback.

PRO-LOCA development under MERIT program mainly addressed three issues;

1) technical improvement of the code including updates to the crack initiation and growth models, WRS distributions as well as implementation of advanced probabilistic routines, e.g., discrete probability methods and importance sampling,
2) sensitivity analyses and quality assurance (QA) checks of the deterministic modules in PRO-LOCA against other codes for ensuring the correctness of implemented algorithms,
3) development of the PRO-LOCA documentation [4] which included the technical basis of the code and the user manual (including the GUI interface).

In particular, a release of the PRO-LOCA documentation was of the great importance as it facilitated for the TAG members to run the PRO-LOCA code with either pre-defined benchmark cases or with their own cases. This provided a valuable feedback to the code developers and the TAG members had a possibility to get a deeper insight into PRO-LOCA capabilities.

Under the MERIT program a vast number of updates was implemented to different models, resulting in release of next version of the code, the PRO-LOCA 2.0. These updates included improvements to crack initiation and growth models, WRS distribution inputs, possibility to account for past and future inspections, the addition of importance sampling, and bootstrap methods for predicting confidence limits on output. A detailed review of the PRO-LOCA development under MERIT program has been presented at the 2009 ASME PVP conference [5].

Further, the PRO-LOCA 2.0 code was used for sensitivity analyses investigating the effect of uncertainty in WRS on the predicted leak and rupture probabilities. The analyses were performed for a DMW case at a hot-leg outlet nozzle assuming PWSCC to be the only active degradation mechanism. The obtained results demonstrated an importance of accounting for the WRS uncertainty in the analyses. Thus, an increase in the mean WRS at the inner pipe surface showed higher, up to two orders of magnitude, leak probability and occurrence of a large-break LOCA [5].

After releasing the PRO-LOCA 2.0 code for MERIT program participants, the nuclear industry and the U.S. government have initiated another research program under the sponsorship of the USNRC and EPRI. This program entitled Extremely Low Probability of Rupture (xLPR) is aimed at developing a new probabilistic fracture mechanics code, also named xLPR after the program title [7]. The xLPR code is intended to demonstrate compliance with 10CFR50 Appendix A, General Design Criteria 4 (GDC-4) that allows for excluding the dynamic effects associated with postulated ruptures of primary piping systems if extremely low probability of rupture can be assured. The Leak-Before-Break deterministic procedures (SRP 3.6.3) can be used to demonstrate compliance with the GDC-4 requirement but do not allow for assessment of piping systems with active degradation mechanisms such as PWSCC. Currently there is no alternative assessment methodology or tool existing that can accommodate active degradation mechanisms and *quantitatively* assess compliance with the GDC-4 requirement. The xLPR code is intended to potentially fill this gap.

As discussed earlier, the PRO-LOCA code development has been motivated by a need to quantify LOCA probabilities for different pipe sizes and to establish the risk-informed approach to the design-basis break size requirements in 10 CFR 50.46 instead of postulating DEGB event of the largest primary piping system.

So, both PFM codes, PRO-LOCA and xLPR, are being developed having different underlying motivation but ultimately the same common goal – *quantitative assessment of leak and rupture probabilities* in nuclear piping systems. All this might lead to confusion about the reasons of having two similar PFM codes and require an explanation of interaction and relationship between xLPR and PRO-LOCA.

While many improvements have been made to PRO-LOCA 2.0 under MERIT program, it still should be considered as a research code rather than a regulatory tool due to the following reasons. Firstly, the PRO-LOCA code includes several legacy codes like SQUIRT, NRCPIPE and others that have been incorporated in their entirety into PRO-LOCA. This approach has turned out to be somewhat problematic for maintaining a neat code structure and created some ambiguity issues as the same parameter has a different variable name in different legacy codes [4]. Secondly, PRO-LOCA has inadequate level of quality assurance (QA) which does not meet the requirements of ASME NQA-1 [6] thereby limiting the use of PRO-LOCA as a general tool.

On the contrary, the xLPR code is being developed in a strict quality assured manner to facilitate its use in a regulatory environment. The xLPR code also has a modular-based architecture with individual deterministic modules placed in a probabilistic software framework. Owing to the complexity of the xLPR code, its development has initially been planned as a two-step process beginning with narrowly defined pilot case study and followed by a more detailed study where analysis procedures will be generalised.

The first step in the xLPR development has been completed providing a first version of the xLPR 1.0 code [7]. Several deterministic models from PRO-LOCA 2.0 and some legacy codes which provide the underlying physics and fracture mechanics basis have been shared with the xLPR code, e.g.:

- Stress intensity K-solutions for surface crack (SC) and through-wall crack (TWC)
- TWC stability model
- Crack opening displacement (COD) model
- Leak rate code (SQUIRT)

The experience from development and application of PRO-LOCA has also been taken into account during the development of the xLPR 1.0 code. Due to issues with quality assurance in PRO-LOCA, the additional quality checks, proper documentation of technical bases and even re-coding may be required for some models/modules before incorporation into xLPR.

2.2.3 PARTRIDGE program (PRO-LOCA 3.0 and 4.0)

PRO-LOCA has also benefited from the xLPR development. Thus, a more advanced PWSCC crack initiation and growth models developed for the xLPR 1.0 code has been incorporated in PRO-LOCA. Other significant improvements to PRO-LOCA from the xLPR development include the improved crack detection procedure (based on probability of non-detection), the updated SC and TWC stability models with faster convergence, representation of weld residual stress profiles by both 3rd polynomial function and Universal Weight Function Method

(UWFM) [8]. With these enhancements the next version of the code, the PRO-LOCA 3.0, was released.

At this time it was seen appropriate to continue the development of both codes in parallel and in close interaction between the research teams. Thus, the models improved under xLPR development could be plugged back in to enhance the PRO-LOCA. On the other hand, the PRO-LOCA, which has reached a more matured development stage and already been introduced for international community through MERIT program, could be used by a larger group of end-users and could provide support to xLPR development. PRO-LOCA can also provide an alternative platform for testing and investigating models without the consensus and QA restrictions of the xLPR development process.

In order to continue further development of the PRO-LOCA code and to provide a mechanism for interaction with the xLPR project, in 2012 a new international cooperative program was established under the name Probabilistic Analysis as a Regulatory Tool for Risk-Informed Decision GuidancE (PARTRIDGE).

The program has been financed by an international consortium representing Canada, United States, South Korea, Taiwan and Sweden. The members of PARTRIDGE program are U.S.NRC, EPRI, CANDU Energy, SSM, Institute of Nuclear Energy Research in Taiwan and a Korean Consortium including Korea Institute of Nuclear Safety, KHNP-CRI, and KEPCO E&C. The technical development of PRO-LOCA under PARTRIDGE program has been performed by Battelle in conjunction with EMC^2.

Both research programs (PARTRIDGE and xLPR) include common participation of NRC and EPRI. Also, the staff members from Battelle and EMC^2 responsible for the PRO-LOCA development actively participate in the xLPR technical task groups. This ensures good interaction and information flow between PRO-LOCA and xLPR.

In brief, further development of PRO-LOCA under PARTRIDGE program will provide an analysis tool that has its basis in the same technical tools as the state-of-the-art code xLPR 2.0 that is being developed by NRC and EPRI. However, PRO-LOCA will include models and tools that are of importance to not only NRC and ERPI but the international participants in PARTRIDGE as well. For example, NRC has little interest in a model of a CANDU reactor but other participants may have significant interest. While developing models for such alternative piping systems and their associated degradation mechanisms, new techniques that are developed will be available to the xLPR team [8].

The following objectives for PARTRIDGE program have been formulated;

- Provide QA support to the xLPR 2.0 code development process
- Further develop the PRO-LOCA code by
  - Enhancing the QA basis and technical documentation basis
  - Incorporating new deterministic modules being developed as part of xLPR into PRO-LOCA (e.g. new leak rate code)
  - Further developing of a PRO-LOCA GUI and User Manual
- Provide a mechanism by which the international community can support the development of the xLPR code

Development of PRO-LOCA under the PARTRIDGE program has included among others the following improvements; (i) implementation of the adaptive sampling method, (ii) the new solutions for K_I and COD for non-idealized TWC, (iii) the new combined pressure and bending COD solutions, (iv) incorporating the modified SQUIRT 3.0 code, (v) implementing the universal weight function method (UWFM) for handling the WRS distribution. With these enhancements to the code under PARTRIDGE program the next version, the PRO-LOCA 4.0, was released in the middle of 2015.

The technical details of PRO-LOCA 4.0 development under PARTRIDGE program will be given in the following sections.

2.3 Objective

Inspecta Technology AB has been commissioned by the Swedish Nuclear Utility Analysis Group (BG) and by the SSM (at the final stage of the project) for:

- Following the PRO-LOCA development;
- Reviewing the technical basis for different modules (e.g. crack initiation, growth, etc.) included in the code;
- Performing benchmark and sensitivity analyses in order to assess general behaviour of the code and adequacy of demonstrated trends;
- Evaluating the project importance and relevance for Swedish nuclear industry and regulatory work.

2.4 Report structure

The organization of this report is described below.

The project information is summarised in Section 1 providing a clear description of the Inspecta assignment, the roles and responsibilities for all involved parties.

Section 2 provides a brief background for PRO-LOCA followed by description of the different stages in the code development. This section also highlights an interaction between the PRO-LOCA code and the xLPR code which is being developed in parallel. Finally, the objectives and scope of this report are defined. The Section 2 can be recommended for reading for those who have little or no information about the PRO-LOCA code.

Section 3 presents the current state-of-the-art technical basis of the PRO-LOCA code. This section also summarises the main improvements and changes introduced into PRO-LOCA as a result of PARTRIDGE program.

Section 4 gives a short introduction to practical aspects of using the PRO-LOCA code for probabilistic analyses. Mainly the topics and issues related to constructing of the input files for PRO-LOCA analysis and post-processing of the obtained results are covered.

In Sections 5 and 6 the benchmark analyses and parametric sensitivity studies are presented based on two cases representing a typical PWR pipe subject to PWSCC degradation and a typical BWR pipe under fatigue cracking. These sections cover different aspects of PRO-LOCA capabilities and underlying models. The adequacy of the observed trends is discussed.

Section 7 discusses the relevance and importance of using PRO-LOCA and other PFM codes for the Swedish nuclear industry and regulatory body. This discussion is placed in a context of existing requirements and applications of probabilistic approaches but also new challenges that may arise and new requirements that may become necessary.

Finally, Section 8 provides discussion and conclusions from this study.

3 Technical basis of PRO-LOCA

The Section 2 of this report provided the historical perspective of PRO-LOCA development which can generally be divided into three stages, referred here as the “early” development [2], MERIT [4][5] and PARTRIDGE [8][9]. This section is intended to provide a review of current technical basis for different models included in PRO-LOCA.

Mainly the latest development of PRO-LOCA under PARTRIDGE program will be addressed, beginning from the PRO-LOCA 3.0 to the latest PRO-LOCA 4.1.9 code which has been released to the technical advisory group (TAG) members in February 2015.

3.1 Status of PRO-LOCA 3.0

Based on the benchmark study [8] of PRO-LOCA against xLPR 1.0, the PRO-LOCA 2.0 code has been updated to the next version, PRO-LOCA 3.0. The PRO-LOCA 3.0 code included the following enhancements:

- new TWC stability model;
- new SC stability model;
- new PWSCC crack growth model;
- new PWSCC crack initiation model;
- new scheme for accounting for the effects of inspection based on the probability of non-detection (PoND);
- new routine for crack placement;
- new scheme for accounting for crack coalescence;
- new WRS module.

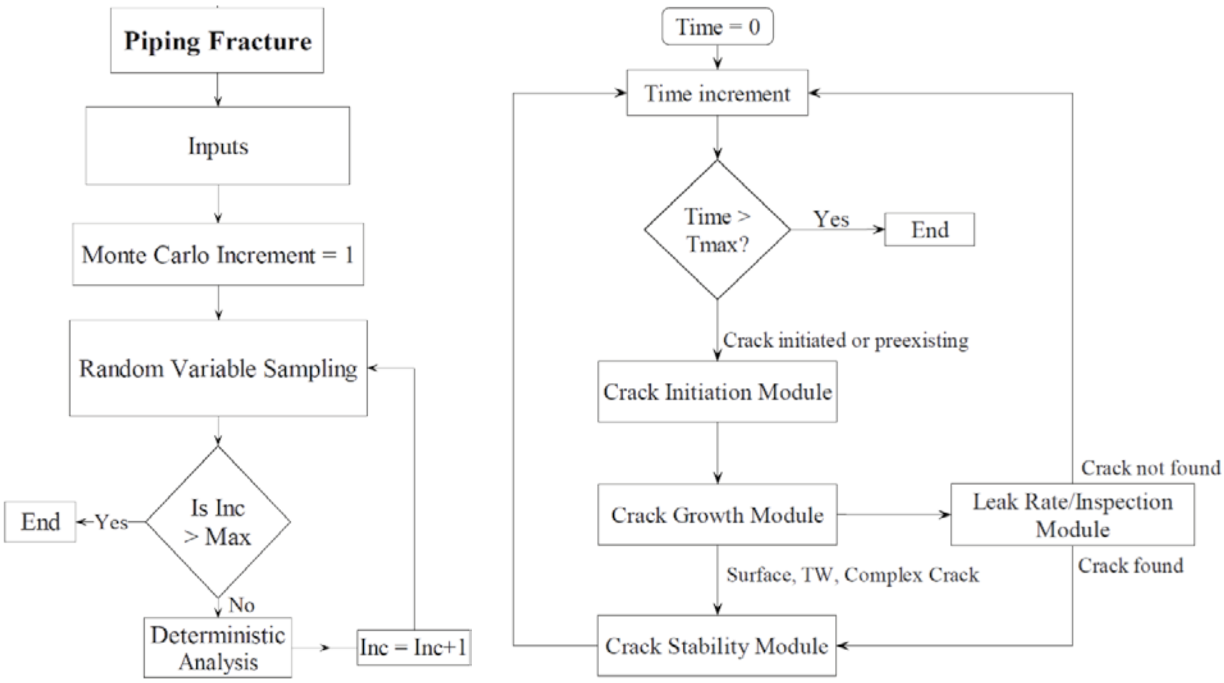
In addition, all routines have been transformed from FORTRAN 77 to FORTRAN 90 allowing for an easier transition between PROLOCA 3.0 (and future versions) and xLPR 2.0 [10].

3.2 Code structure and probabilistic frame-work

The code structure has in general been unchanged since the release of PRO-LOCA 1.0. A flow chart providing a top-level insight into PRO-LOCA structure is presented in Figure 1(a). In PRO-LOCA a probabilistic numerical scheme is used for solving the multiple deterministic analyses by repeatedly sampling values from the probability distributions for the uncertain variables. A more detailed flow chart of the deterministic modules of the PRO-LOCA code is shown in Figure 1(b).

There are several probabilistic simulation schemes included in PRO-LOCA. The traditional Monte-Carlo (MC) simulation and the discrete probability density (DPD) methods including importance sampling were implemented in the PRO-LOCA 3.0 and are fully documented in the MERIT final report [4]. The use of traditional MC simulation is generally associated with a concern on how many iterations are needed to obtain convergence and confidence in results. As a general practice, it is recommended to perform analyses with number of MC iterations exceeding the probability value of interest by one order of magnitude. Thus, 10^6 MC iterations are required for analysis of a pipe rupture with probability of 10^{-5} (1 event in 100,000).

Under PARTRIDGE program, the adaptive sampling method has been developed and implemented in the PRO-LOCA 4.0 code. The adaptive sampling allows the simulation method to adapt to the calculated responses and adjust the DPD to focus the sampling on the regions of most interest. By employing this approach, the very low probability events ($< 10^{-8}$) can be assessed at reasonable time effort. The technical details and basis of this approach are provided in e.g. [11] [12]. The efficiency of the adaptive sampling scheme has been evaluated for an analysis of nuclear piping fracture in [11]. It was shown that the adaptive sampling can reproduce the results from the



traditional Monte Carlo simulation with a factor of 400 fewer samples.

(a) (b)

Figure 1 (a) Overall code structure and (b) detailed flow chart for the deterministic analysis procedure of the PRO-LOCA code [5].

3.3 Geometric model

The geometric model used in PRO-LOCA has remained without modifications in PARTRIDGE program. In brief, PRO-LOCA allows for analysis of only one critical location or node during each run. One node consists of one circumferential section of the pipe (typically a circumferential girth weld) in the piping system. If the leakage or rupture probability for the entire system is desired, the PRO-LOCA analyses have to be performed for all nodes (welds) followed by summing up the individual node probabilities to get the total system probability.

For tracking the crack initiation and growth, the circumference of a critical node is broken down into subunits. The size of the subunits is based on a fix percentage of the pipe circumference. Currently that percentage is approximately based on a 50 mm long subunit for a 28-inch diameter pipe.

The implemented geometric model in PRO-LOCA is fully documented in the MERIT final report [4].

3.4 Crack initiation models

PRO-LOCA from the "early" development stage had the default crack initiation models for thermal fatigue and stress corrosion cracking (including PWSCC and IGSCC). These models for crack initiation are phenomenological and based on experimental research work performed by Argonne National Lab (ANL). The crack initiation models for PWSCC and IGSCC are considered to be a statistical process described by Weibull distribution applied to service history data. The default models for crack initiation are fully documented in the MERIT final report [4].

In addition to default crack initiation models, the user defined models were implemented in PRO-LOCA under MERIT program. The user defined models for crack initiation included (1) singe crack and (2) multiple crack models and (3) Poisson arrival rate model. Each of the user defined models had several options for controlling the time to initiation including the distribution type, probabilistically defined parameters for initial crack length and depth, and arrival rate for circumferential cracks per year [4][5].

Under PARTRIDGE program, no substantial changes were made to the default crack initiation models. These models are now denoted as PROLOCA 2005 models in the User Manual for the latest released version of PRO-LOCA 4.1.9 [13].

Some minor modifications have been implemented into the user defined crack initiation models. Thus, the single and multiple crack models were merged into one model, denoted now as initial distribution model where user can control the time to initiation (usually assumed to be Weibull, but other types are available) and the initial crack length and depth.

For summary, the PRO-LOCA code after the PARTIRDGE program has three crack initiation models implemented [13];

- PROLOCA 2005 initiation model
- Initiation distribution
- Poisson arrival rate

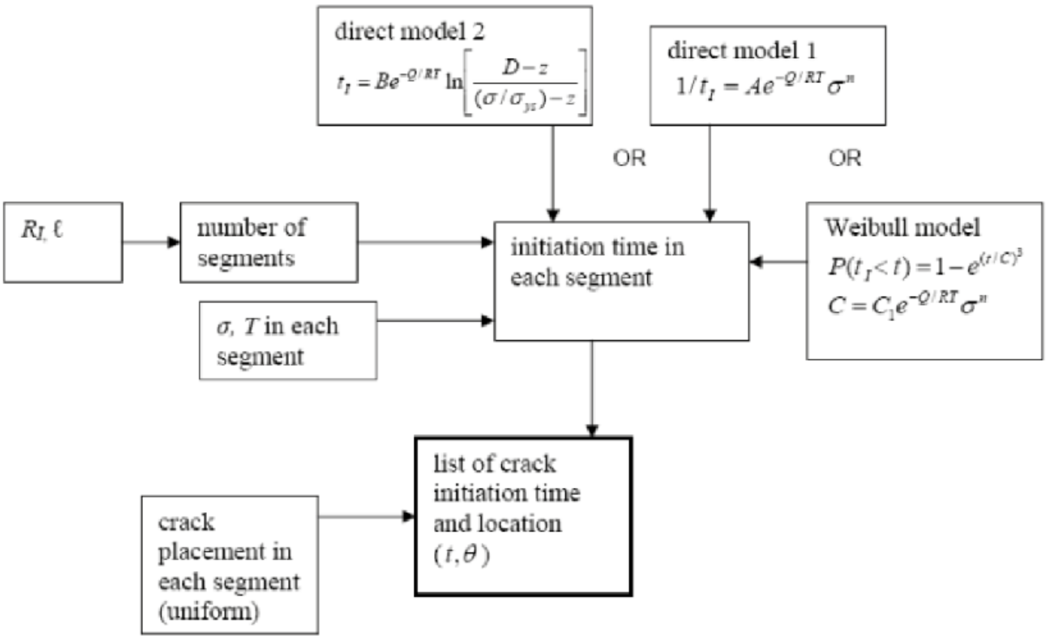


Figure 2 PWSCC crack initiation model implemented in the xLPR 1.0 code [7].

Under PARTRIDGE program there was a task defined for including a more advanced initiation model for PWSCC crack which was developed for xLPR 1.0 [7]. This model as schematically shown in Figure 2 incorporates three separate models, where two of them are time-based models and the third is a Weibull model, all being corrected for temperature and stress. The model is rather complicated and requires a calibration to either laboratory or service-based crack initiation data. In the xLPR study the calibration was performed only to the service data providing an arrival rate of about 0.01 cracks/year. It was considered that the xLPR model in the current level of development will provide little value to PRO-LOCA as initiation of multiple PWSCC cracks can be well represented by Poisson arrival rate model. However, it is expected that the xLPR PWSCC model will be included into PRO-LOCA in future.

3.5 Crack growth models

PRO-LOCA from "early" development stage had several default crack growth models capable of treating thermal fatigue (including air and reactor water environments) and stress corrosion cracking (including PWSCC and IGSCC). These models were phenomenologically described and based on experimental research work performed by Argonne National Lab (ANL). The technical basis of the default crack growth models along with underlying references is thoroughly documented in the MERIT final report [4].

Under MERIT program, user defined crack growth laws for fatigue and SCC were implemented into the PRO-LOCA code using the following basic forms;

$\mathrm{d}a/\mathrm{d}t = C \cdot (K - K_{\mathrm{th}})^{\mathrm{m}}$	SCC law with both a K-plateau and a K-threshold defined for no crack growth
$\mathrm{d}a/\mathrm{d}N = C \cdot (\Delta K)^{\mathrm{m}}$	Fatigue law with a ΔK-threshold defined for no crack growth

In these models only the crack growth coefficients (C) were described as distributed variables. Other parameters including the crack growth exponent (m), the K-values for plateau (SCC), and the K-threshold values were treated as deterministic variables [4].

Under the PARTRIRDGE program, the user defined models were updated so that even the crack growth exponent (m) and K-threshold values for both fatigue and SCC laws are defined as distributed probabilistic variables (PRO-LOCA 4.1.9 [13]).

In addition to the existing default pre-programmed (based on ANL work) and user defined (based on Paris law) fatigue models, several other fatigue crack growth laws including Forman law, Walker law, NUREG-CR/6986 and NUREG-CR/6674 models were introduced in the PRO-LOCA code [12]. The included fatigue crack growth laws were not reviewed in this report and therefore the underlying references are provided in this report. The references describing the technical basis for above mentioned models can be found in study [9].

In addition to the existing default and user defined SCC models, a more advanced PWSCC growth model from the xLPR 1.0 code was implemented into PRO-LOCA. The xLPR 1.0 model has been developed by EPRI under the Material Reliability Program MRP-115 dealing with crack growth characterisation under PWSCC in Alloy 82 and 182 welds [14]. This model is based on a linearized, multiple regression statistical data fit approach that includes an Arrhenius temperature correction, a crack orientation factor (parallel or perpendicular to the weld dendrites), a crack tip stress intensity factor exponent, and takes into account an uncertainty associated with the heat of weld wire/stick material and welding process.

The xLPR 1.0 PWSCC model is given by;

$$\frac{\mathrm{d}a}{\mathrm{d}t} = e^{-\left[\frac{Q_g}{R}\cdot\left(\frac{1}{T+273.15}-\frac{1}{T_{\mathrm{ref}}}\right)\right]} \cdot \alpha \cdot f_{weld} \cdot f_{ww} \cdot (K_{\mathrm{I}} - K_{\mathrm{Ith}})^{\beta}$$

where

${}^{\mathrm{d}a}/_{\mathrm{d}t}$	crack growth rate $(\mathrm{m/s})$
Q_g	thermal activation energy for crack growth $(\mathrm{kJ/mole})$
R	universal gas constant equal to $8.314{\cdot}10^{-3}$ $\mathrm{kJ/(mole{\cdot}}K)$
T	temperature at location of crack (°C)
T_{ref}	absolute reference temperature used to normalize data $(598.15\ K)$
α	power-law coefficient $((\mathrm{m/s})(\mathrm{MPa}\sqrt{\mathrm{m}})^{\beta})$
f_{weld}	common factor applied to all specimens fabricated from the same weld to account for weld wire/stick heat processing and for weld fabrication
f_{ww}	"within weld" factor that accounts for the variability in crack growth rate for different specimens fabricated from the same weld (1.0 for deterministic approach)
K_{I}	crack-tip stress intensity factor $(\mathrm{MPa}\sqrt{\mathrm{m}})$
K_{Ith}	crack-tip stress intensity factor threshold, below which is zero $(\mathrm{MPa}\sqrt{\mathrm{m}})$
β	stress intensity factor exponent

The xLPR 1.0 PWSCC model was incorporated in the PRO-LOCA v. 4.1 as given by Eq. (1) apart from treating the parameters f_{weld} and f_{ww} as a single random variable denoted f_{weld} [12]. Later, the PWSCC model was updated to include the effect of dissolved hydrogen concentration based on EPRI MPR-263 research on chemical mitigation of primary water stress corrosion cracking [15]. This updated PWSCC model was incorporated in PRO-LOCA 4.1.9.

An interesting comparison between the developed xLPR 1.0 PWSCC growth model and other PWSCC models is reproduced from the EPRI

MRP-115 study [14] in Figure 3. It is worth and relevant for Swedish nuclear industry to highlight a difference between a Ringhals two-part curve and the xLPR 1.0 MRP-115 curve, both for Alloy 182. The Ringhals curve assumes no crack growth below the threshold value of about $K_{\mathrm{Ith}} = 13\ \mathrm{MPa}\sqrt{\mathrm{m}}$. For stress intensity factors above the threshold value, the Ringhals curve predicts significantly lower crack growth rates in comparison to the MRP-115 curve besides the region of K-values in a range 22-40 $\mathrm{MPa}\sqrt{\mathrm{m}}$ where the growth rates are higher than for the MRP-115 curve.

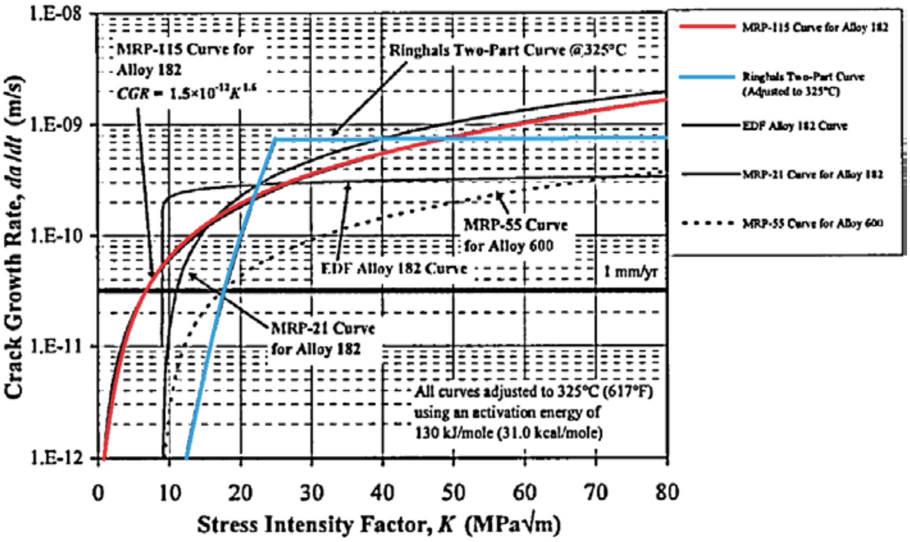


Figure 3 Comparison of the xLPR 1.0 PWSCC crack growth model for Alloy 182 weld with other models [14].

3.6 Crack transition model

Earlier versions of PRO-LOCA, including the version 3.0 (released under MERIT program), were based on the idealised models for a circumferential surface crack (SC) and a through-wall crack (TWC). Thus, a semi-elliptical shape for the SC and the crack front orthogonal to the pipe wall for the TWC were assumed. Stress intensity factor K_{I} solutions for subcritical crack growth by Anderson were initially implemented in the PRO-LOCA code. Anderson solutions were chosen since they included influence functions for the idealised circumferential SC and TWC in cylinders for a variety of geometry ratios R/t, crack length and depth values. These K-solutions are fully documented in the MERIT report [4].

The through-wall crack transition model used in earlier versions of PRO-LOCA was also idealised. This transition model assumes that once a subcritical 'idealised' SC penetrates the pipe wall it can be re-characterised into an 'idealised' TWC. The length of the through-wall crack is determined based on the equivalent crack area of the surface crack as schematically shown in Figure 4 (a). After transition, an idealised TWC eventually grows with its preserved shape.

Observations of real leaking cracks demonstrated a disagreement with the idealised TWC transition model. In most cases, a substantially longer crack was found on the inside of the pipe than the crack length on the outside suggesting that a TWC after transition from a surface crack grows in a non-idealised manner as shown in Figure 4 (b). A difference in crack length on the inside and outside of the pipe can be especially pronounced for stress corrosion cracking due to distribution of weld residual stresses through the wall thickness.

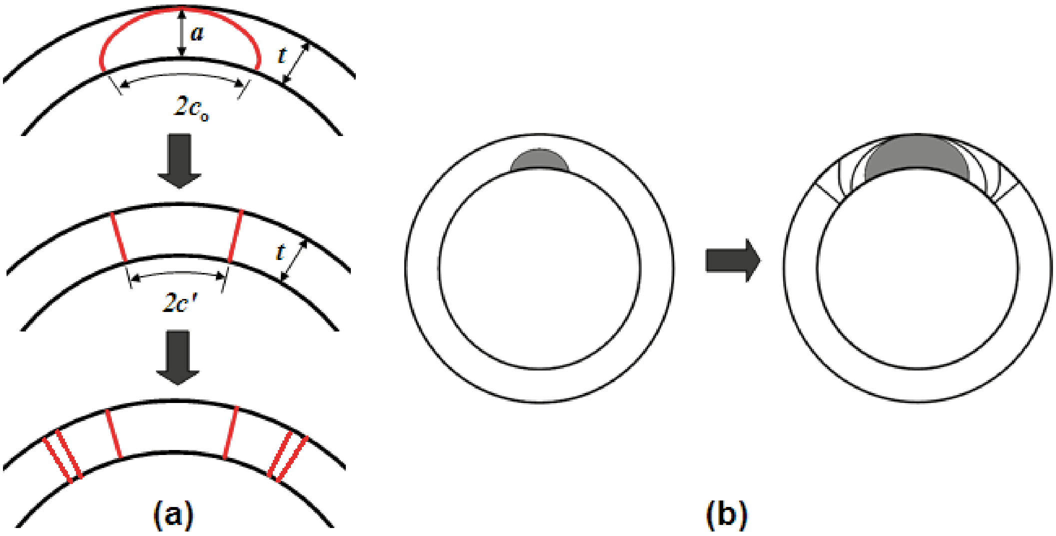


Figure 4 TWC transition models; (a) idealised model based on the equivalent area method and (b) non-idealised model based on natural transition (reproduced with some modifications from [21]).

Non-idealised complex shape of a TWC during transition and growth in the pipe wall was addressed in previous research work conducted 1995 in Sweden [16][17]. In study [16] it was pointed out that a discrepancy between the idealised TWC transition model and real crack morphology can significantly affect the predictions of the crack opening area (COA) and thereby the mass leak rates which is a cornerstone of the leak-before-break (LBB) philosophy. In recent study [18] ‘natural’ crack growth through the pipe wall was simulated by advanced finite element analysis (AFEA). In addition, leak rate predictions for the ‘idealised’ and ‘natural’ transition models have been compared confirming that the idealised TWC transition model gives overestimated mass leak rates.

Obviously, a reliable prediction of mass leak rates should be a paramount feature since PRO-LOCA has been developed as a tool for assessing leakage and rupture frequencies in a risk-informed process of selection of the design basis break size instead of the DEGB criterion. In the light of the above findings, the adequacy of having the idealised TWC crack transition model in PRO-LOCA could be argued emphasizing a need for a more accurate transition model.

Stress intensity factor K and crack opening displacement (COD) solutions for non-idealised TWC transition and subcritical growth through a pipe wall were developed in several studies though limited to certain ratios of R/t, crack sizes and loadings. Thus, a procedure was suggested in [16] for predicting the subcritical growth of a non-idealised circumferential surface crack through a pipe wall for pipe geometries with R_{i}/t =9 under fatigue and stress corrosion. This procedure was also implemented in a computer program LBBPIPE capable of calculating crack sizes and mass leak rates as a function of time and also predicting leakage and final failure [16]. Benchmarking of the developed procedure and the LBBPIPE code against available data from fatigue-loaded pipes was performed in the study [17] as a part of the SINTAP project demonstrating a good agreement. In more recent study [19] the K-factor and COD solutions were developed for a circumferential slanted TWC in a pipe considering axial tension, global bending and internal pressure loadings. While the presented solutions covered two different pipe geometries $R_{\mathrm{m}}/t = 5$ and $R_{\mathrm{m}}/t = 10$, only limited crack sizes were considered.

Under the PARTIRDGE program, new K and COD solutions have been developed for non-idealised TWC growth for both a circumferential and axial cracks covering a wide range of pipe geometries, crack sizes and loads. These solutions were obtained as in kind research contribution by the Korean consortium and implemented into PRO-LOCA 4.0 [9][21]. Further, a new crack transition model was developed for PRO-LOCA using the non-idealized TWC solutions to more accurately capture the crack transition behaviour [20].

New solutions for a non-idealised TWC growth are presented in detail in Ref. [9] and non-idealised surface to through-wall crack transition model is discussed in Ref.[20]. Therefore, only a brief summary of both models is given below.

3.6.1 Solutions for non-idealised TWC in pipe

The non-idealized TWC with different crack length on the inside and outside of a pipe is represented by the half crack angles θ_1 and θ_2, respectively, as shown in Figure 5. At the moment when a surface crack penetrates the wall thickness, the angle ratio is typically θ_1/θ_2 >1 and for a fully penetrated TWC (idealised TWC) the angle ratio $\theta_1/\theta_2 = 1$.

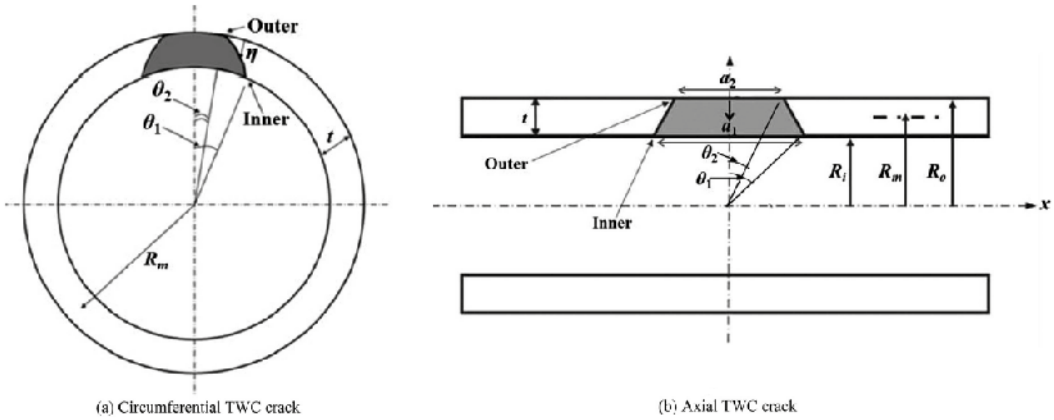


Figure 5 A schematic of non-idealised TWC (reproduced from Ref. [9]).

In order to correlate K_{I} and COD of the idealised TWC with the corresponding values for the non-idealised TWC the correction factors, G and V, were introduced as follows;

$$K_{\mathrm{I},i}^{\text{non-idealised}} = G_i \cdot K_{\mathrm{I},i}^{\text{idealised}}$$

$$\delta_i^{\text{non-idealised}} = V_i \cdot \frac{4\sigma R_m \theta_i}{E}$$

where σ is the applied load (i.e. axial tension, global bending, internal pressure), and subscript 'i' defines the specific location through the thickness (1 for inner surface, m for middle thickness, and 2 for outer surface).

A series of 3D elastic finite element (FE) analyses were performed to obtain K_{I} and COD values for non-idealized and idealized TWCs, respectively. The K_{I} values at the inner and outer surface were fitted by a polynomial function so that the correlation factors G and V could be calculated using Eqs. (2, 3). The FE analyses were performed for a range of ratios R_{m}/t, θ_1/π, and θ_1/θ_2 selected to cover practical pipe sizes and crack shapes. The obtained solutions for K_{I} and COD are valid within the limits for used ratios as given in Table 1. For geometries outside the valid range, it is recommended to use the bounding values.

Table 1 Validity limits of the non-idealised TWC solutions for K_{I} and COD.

TWC orientation	Load type	R_m/t	θ_1/π	θ_1/θ_2
Circumferential	Axial tension, global bending	$2, 5, 10, 20$	$0.125, 0.25, 0.3, 0.4, 0.5$	$1, 1.5, 2, 3, 4$
Axial*	Internal pressure	$2, 5, 10, 20$	$0.5, 1, 2, 3$	$1, 1.5, 2, 3, 4$

*) It is worth to point out here that while the obtained solutions for K_{I} and COD cover both TWC orientations, PRO-LOCA can currently handle only circumferential flaws.

The values of derived correlation factors G_1, G_2, $V_1$and V_2 for all analysed cases in Table 1 were provided to PARTRIDGE program for implementation in PRO-LOCA 4.0 and xLPR 2.0 codes. The correlation factors for non-idealised TWC crack solutions were also justified by the results of natural crack growth analyses conducted by Emc2. The comparison demonstrated that the proposed G and V factors are slightly conservative compared to the results of natural crack growth analysis [9].

3.6.2 PRO-LOCA 4.0 crack transition model

Developed K and COD solutions for non-idealised circumferential TWC in pipe were used for the new crack transition model. This model transitions a sub-critical surface crack to an initial non-idealized TWC. Note that this model assumes that there is no ductile tearing or local ligament collapse. Once the initial non-idealized TWC has been determined, then K and COD solutions for non-idealized TWC are used to continue the crack growth of the non-idealized TWC. A step-by-step procedure for the crack transition model is discussed in detail in Ref. [20] and briefly summarised below.

Step 1 – Final surface crack to initial non-idealized TWC

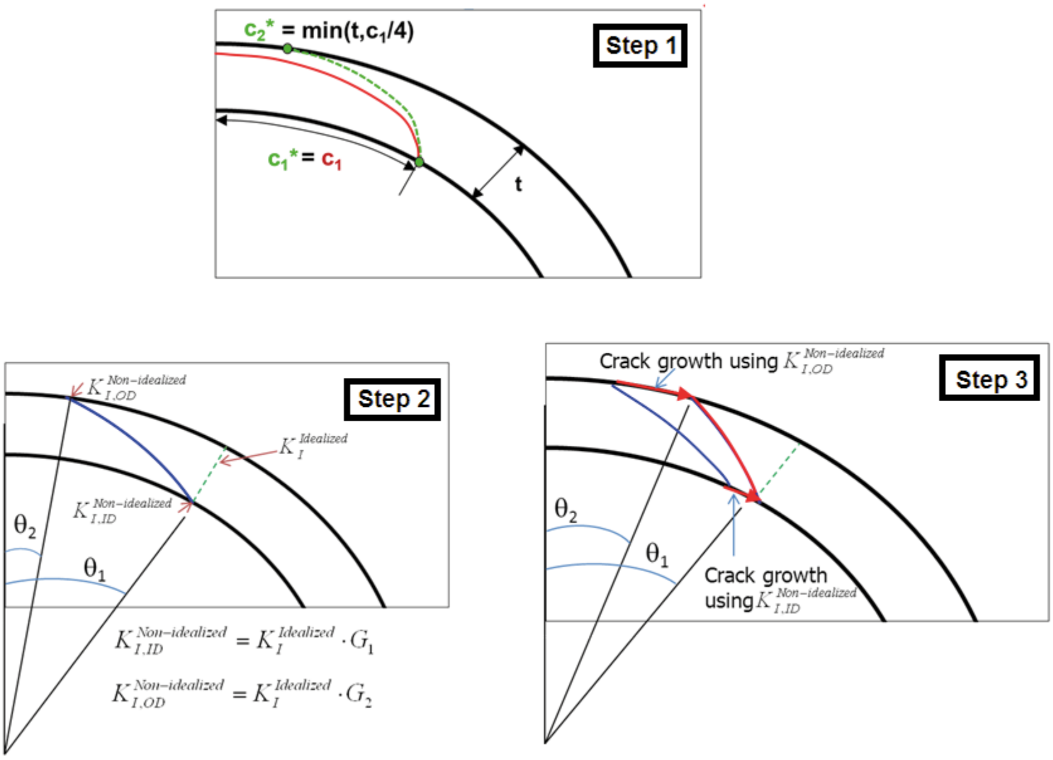
A transition of the sub-critical surface crack to the initial non-idealized TWC is assumed to occur once the surface crack depth reaches 95% of the wall thickness based on the guidance provided in R6 procedure. The crack lengths at ID and OD surfaces of the initial non-idealized TWC are determined as shown in Figure 6 (Step 1). Note that once the ID and OD crack lengths have been determined, the crack front shape will be assumed to be slightly curved due to cylindrical transformation, as was used for the development of non-idealized TWC K and COD solutions [9].

STEP 2 – Calculation of K and COD

Values of K and COD at the ID and OD surfaces can be calculated for the determined ID and OD crack lengths using the non-idealized K and COD solutions [9]. First, the $K^{\mathrm{idealised}}$ value for the idealized

TWC with the same length (or angle) on the ID surface (dashed line in Figure 6 (Step 2)) is calculated. Then, the correction factors (G_1 and G_2), which are functions of R_m/t, θ_1/π, and θ_1/θ_2 and loading type, are calculated for the ID and OD points of the non-idealized TWC. Since the G values are provided for single loading conditions, decomposition of applied load (or stress) may be required. The K values at the ID and OD surfaces are calculated for each loading condition and the total K value is obtained through superposition of all loading conditions. The COD values for the non-idealized TWC are obtained in similar way.

Figure 6 Non-idealised surface to through-wall crack transition model in



PRO-LOCA 4.0 (reproduced from Ref. [21]).

Step 3 – Crack growth calculation

Once the K and COD values are calculated for both the ID and OD surface points of the non-idealized TWC, the crack is grown at the ID and OD points to obtain the next non-idealized TWC as shown in Figure 6 (Step 3). Now, a new set of θ_1/π and θ_1/θ_2 values is obtained so the new K and COD values are repeatedly calculated using the Step 2 above. When the ratio becomes $\theta_1/\theta_2 = 1.05$, the non-idealised TWC is re-characterised to the idealised TWC so the classical Anderson solutions for K and COD can be used. The criterion for re-characterisation of the TWC crack from non-idealised to idealised at $\theta_1/\theta_2 = 1.05$ is determined from natural crack growth observations [18].

3.7 Crack coalescence scheme

The crack coalescence scheme is an important part of PRO-LOCA ensuring that the cracks developed during analysis can be representative of the long surface cracks found in service. The scheme was developed for PRO-LOCA 2.0 under MERIT program [4]. Thus, circumferential surface cracks will coalesce when the distance between them becomes $S < 2 \cdot \max(d_1, d_2)$, where d_1 and d_2 are the depths of considered SCs. The depth of the new crack is set equal to the deepest SC and the length is equal $L = l_1 + l_2 + S$. Through-wall cracks will coalesce when the crack tips touch.

Under PARTRIDGE program, no further development of this crack coalescence scheme was performed apart from modifying the PROLOCA 2.0 model to include the new rules from ASME XI 2013, IWA-3000. In PRO-LOCA 4.0 it is assumed that two surface cracks will coalesce when the distance between them becomes $S < 0.5 \cdot \max(d_1, d_2)$. For TWCs, the coalescence scheme remains unchanged from the PRO-LOCA 2.0 model [12].

3.8 Crack stability model

A crack stability model is used to determine if any existing cracks have reached a critical size. The module, implemented in PRO-LOCA 2.0 under MERIT program, can analyse the stability of a surface crack, through-wall crack, and complex crack (full circumferential surface crack with a finite depth through the pipe wall which has penetrated the pipe wall thickness for a segment of the pipe circumference). The crack stability module in PRO.LOCA 2.0 included the following models:

- Screening criterion for a simple stability check based on Dimensionless Plastic Zone Parameter (DPZP)
- Surface crack stability based on SC.TNP1 analysis method
- Through-wall crack stability based on LBB.ENG2 analysis method.

PRO-LOCA 2.0 initially performed a stability check using the DPZP screening criterion due to its simple formulation and low CPU cost. If the DPZP criterion fails, a more detailed stability analysis based on J-integral estimation scheme is employed. The detailed models for crack stability assessment are known as the SC.TNP1 model for surface cracks, and the LBB.ENG2 model for through-wall and complex cracks. Both models are based on the J-integral fracture parameter and provide good agreement with pipe fracture experiments. In both models, the non-linear stress-strain behaviour of the base metal is considered using the Ramberg-Osgood relationship and the fracture toughness of the weld metal is given in terms of the $J - R$ curve. In case of a through-wall crack, the GE/EPRI J-estimation scheme is used for calculation of crack opening displacement (COD) and mass leak rates through the crack. These crack stability models in PRO.LOCA 2.0 are thoroughly documented in MERIT final report [4].

The crack stability models in PRO-LOCA were further enhanced during xLPR development and re-named to TWC_Fail and SC_Fail. With implementation of the TWC_Fail and SC_Fail models the use of the DPZP screening criterion was eliminated in PRO-LOCA 3.0 and later versions.

The current version of PRO-LOCA 4.1.9 incorporates the TWC_Fail module that is also used in xLPR 2.0. In this module the critical TWC size is calculated using both the Net-Section Collapse (NSC) and LBB.ENG2 elastic-plastic methods. The solution yielding the smallest critical crack is used for the pass/fail assessment and for calculating the ratio of the current crack size to the critical crack size.

The SC_Fail model is based on two idealised surface crack geometries (the constant depth SC and semi-elliptical SC) as shown in Figure 7. The stability analysis is based on a limit load solution using the Net-Section Collapse method for tension and bending loads [23]. The SC_Fail model is not included in the current version of PRO-LOCA 4.1.9 while it is planned to implement it in future versions. In PROLOCA 4.1.9 a surface crack is deemed to have failed resulting in a TWC when the depth of the surface crack reached a value of 95% of the pipe wall thickness**.**

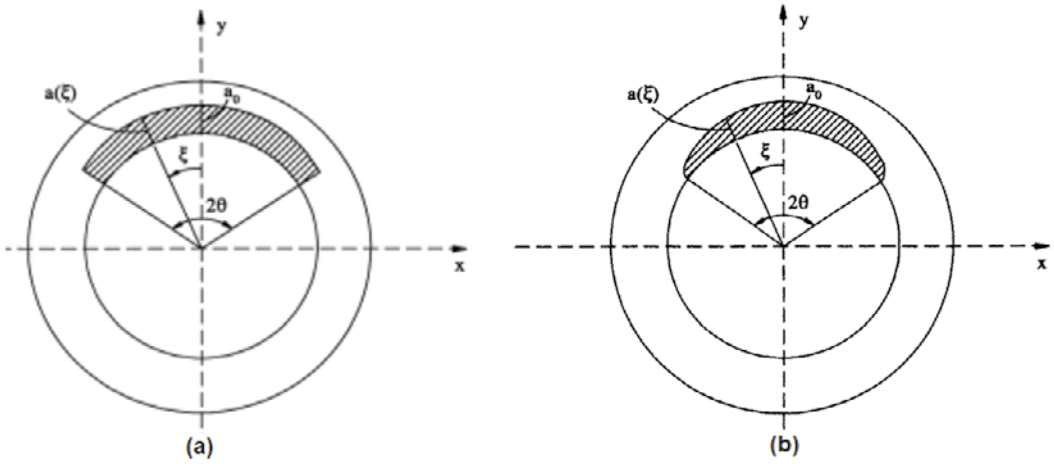


Figure 7 Ideal geometries included in new SC_Fail crack stability model; (a) constant depth SC and (b) Semi-elliptical SC (reproduced from Ref.[22]).

3.9 Crack Opening Displacement (COD) model

Calculation of crack opening displacement (COD) is essential in the prediction of mass leak rates through cracks. Earlier versions of PRO-LOCA (up to and including version 3.0) included only the original GE/EPRI solutions for COD predictions described in e.g. [24]. This method, even though widely used, is based on finite element analyses with structural shell type elements and, therefore, has inherent limitations. Thus, the GE/EPRI COD model cannot account for crack face pressure (CFP) and variation in COD values through the pipe wall. Additionally, it assumes that axial force and bending moment are acting on a pipe simultaneously. The GE/EPRI model is also limited to crack length ratios $\theta/\pi \leq 0.5$ and pipe radius-to-wall thickness ratios $R/t \geq 10$, which is typically found in BWR plants but not representative for PWR geometries.

A more advanced version of GE/EPRI COD model incorporating the new combined pressure and bending COD solutions has been developed by Battelle [25][26]. Under PARTRIDGE program, Battelle COD model was implemented into PRO-LOCA 4.0 in addition to the original GE/EPRI model. The new model is based on a 3D FE model with solid continuum elements in order to determine the elastic and plastic influence functions for the analytical COD formulas in a similar fashion as it was done in the original GE/EPRI model. The Battelle COD model covers a range of pipe sizes, R/t ratios, crack lengths $0.05 \leq \theta/\pi \leq 0.9$ and internal pressures applicable to both BWR and PWR piping. In the Battelle COD model it is assumed that axial load due to pressure and CFP act concurrently and the bending moment is applied subsequent to these pressures. CFP values are proportional to internal pressure and uniform through the wall thickness. Battelle model can predict COD values at 3 locations through the pipe wall thickness, i.e., at the inside surface, at mid wall, and at the outside surface.

Initial validation of Battelle COD model against the original GE/EPRI model and available analytical solutions demonstrated a good agreement [25]. However, the comparisons in Ref. [25] were performed only for pure tension and pure bending cases. Also, the developed solution assumes free-end pipes while the effect of pipe end restraints on the influence functions change will be investigated in future.

Development of plastic influence functions to account for combined tension, crack face pressure and bending loads was in progress but no later publication where the results could be followed was found in open literature. Also, Battelle COD model is based on a number of assumptions that may provide overly-conservative results. The effects of weld residual stresses on COD and possibility to account for variable CFP should be implemented in the model for more accurate COD predictions [25].

3.10 Weld residual stresses

Earlier versions of PRO-LOCA, apart from ASME XI weld residual stress (WRS) recommended distributions, included several geometric specific WRS distributions for six different geometries based on detailed finite element analyses [2]. These geometries included two hot leg-to-RPV nozzle dissimilar welds, the surge line to pressurizer nozzle dissimilar weld, the pressurizer spray line to pressurizer nozzle dissimilar weld, and two stainless-to-stainless weld solutions. In all cases, the WRS values from FE analyses were normalized by the yield strength of the material and fit by a 4th order polynomial function. This normalization allows for the variability in the WRS when PRO-LOCA is sampling on yield strength distribution. Even though this approach may capture the material variability in the WRS, it does not capture other variabilities such as welding parameters and analysis assumptions.

Under MERIT program the PRO-LOCA 2.0 code was enhanced with a two parameter user defined WRS distribution as shown in Figure 8. This model accounts for a distribution of tensile WRS at the inner diameter (ID) of a pipe and a distribution of distance X_c at which the tensile residual stresses first change to compressive stresses. In this model the WRS profile is fitted by a 3rd order polynomial distribution so that the equilibrium through the wall thickness is obtained [4][5].

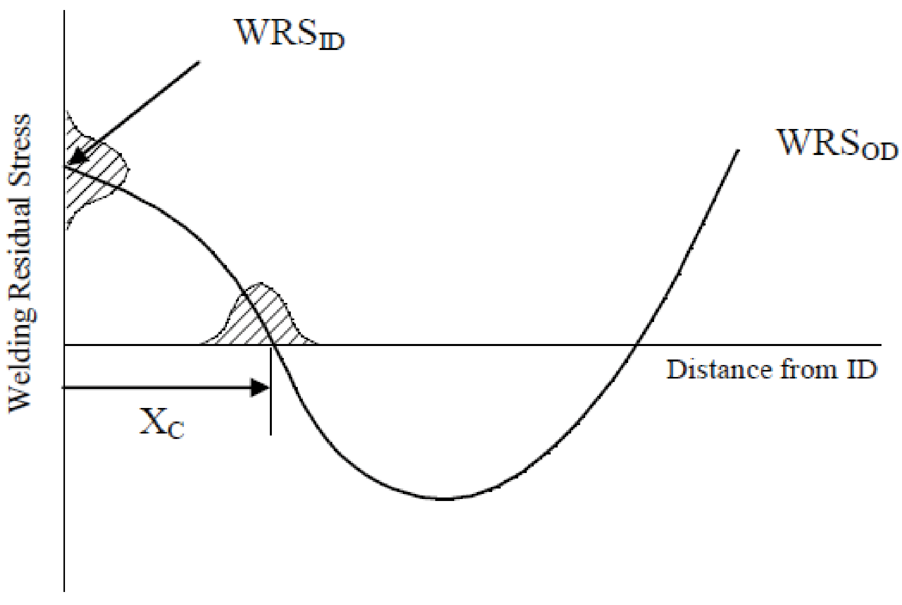


Figure 8 User defined two parameter WRS model (reproduced from Ref.[4]).

The 4th order polynomial fit was suppressed in PRO-LOCA 2.0 as it was found providing unrealistic WRS distributions. Unrealistic weld residual stresses were identified in certain cases even when using the 3rd order polynomial function. Therefore, a bounding method was developed for identifying samples with unrealistic peak values and rejecting them, if the stresses exceed a bounding value. The examples of bounded and unbounded WRS profiles for 3rd and 4th order polynomial functions are presented in Figure 9. The developed bounding method was implemented into PRO-LOCA 3.0 [22].

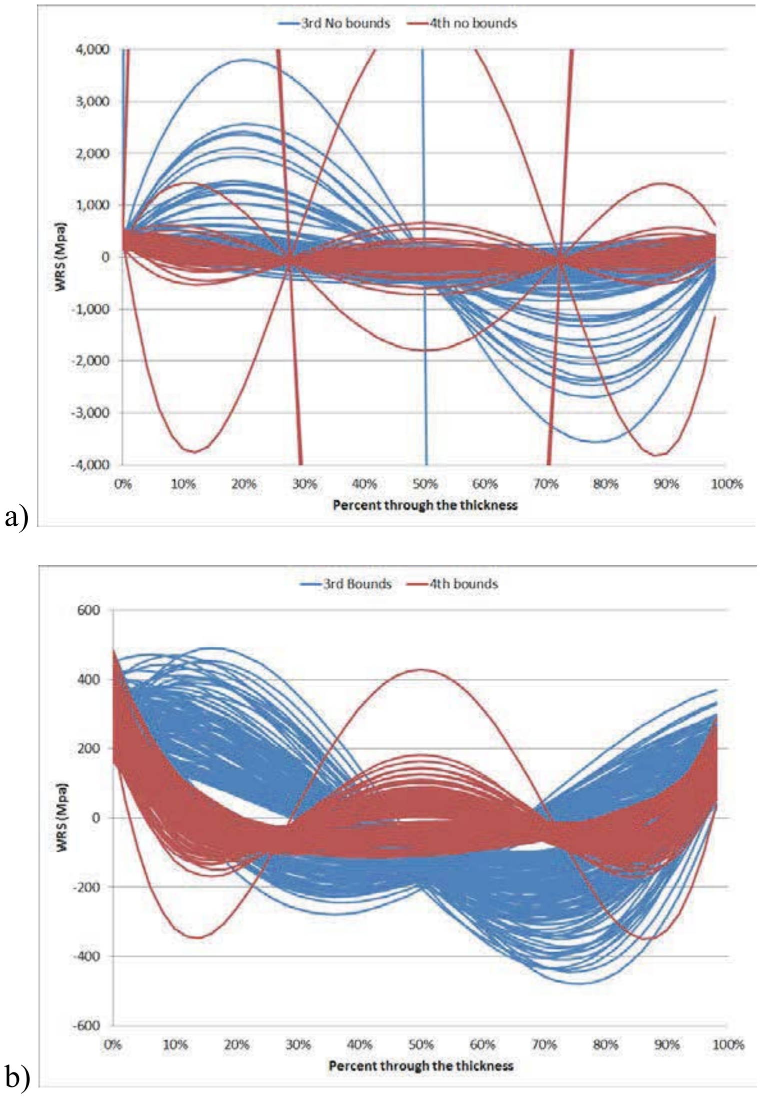


Figure 9 Unbounded vs bounded polynomial WRS distributions (reproduced from Ref.[22]).

Under PARTRIDGE program, an alternative approach using the Universal Weight Function Method (UWFM) for handling the WRS distribution in the thickness direction has been included in PRO-LOCA 4.0 [12]. The UWFM developed under the xLPR 2.0 study does not require a polynomial fit of discrete WRS values as it follows the actual WRS profile. In this method, a piece-wise cubic interpolation of stresses between the discrete locations with known stress values is used to calculate the stress intensity factors K_{I}. The detailed description of the UWFM method can be found in Ref. [27]. The piece-wise WRS representation using the UWFM was compared with the 4th order polynomial WRS representation and with a finite element reference solution [28]. The results of this study demonstrated a good agreement between the UWFM stress representation with FE results while the polynomial fit does not always accurately represent the actual WRS distribution through the thickness.

3.11 Leak rate

The Henry-Fauske leak-rate model that is used in the SQUIRT code is implemented in PRO-LOCA for calculating leak rates in pipes with through-wall cracks. For leak rate calculations, a user is required to input the mean value and standard deviation for the leak-detection limit which is defined using normal distribution. If the current leak rate through an existing crack is greater than the sampled leak detection limit, the leak is assumed to be detected and the crack node is removed from the analysis. Full details regarding the theory and implementation of the leak rate model in PRO-LOCA were given in MERIT final report [4].

SQUIRT model implemented in the PRO-LOCA versions up to and including 3.0 is known to have convergence issues, especially in the range of very low and very large leak rates. Also some discontinuity issues and unrealistic trends have been identified for certain flow regimes in the leak rate versus COD curves [22][29].

Under PARTRIDGE program it was initially planned to develop and implement into PRO-LOCA a look up table for leak rate estimation that accounts for the distribution in the crack morphology parameters. However, after the 1st TAG meeting the look-up table development was eliminated from the work scope in favour to put more effort on developing the methodology for addressing the solutions for COD and K in the crack transition model (see Section 3.6). As a result, it was decided to continue using the SQUIRT code for the leak rate analysis within the PRO-LOCA framework.

Although a limited effort in SQUIRT development was undertaken under PARTIRDGE program. The SQUIRT code was modified to address the discontinuity issues in the leak rate versus COD curves at small COD values. A new interpolation routine addressing this issue was added to the SQUIRT 3.0 module in PRO-LOCA 4.0. Recent comparisons between the modified SQUIRT and the new LEAPOR code developed by ORNL for xLPR 2.0 [30] have shown a very good agreement between the two codes. A comparison of the LEAPOR and the modified SQUIRT codes is shown in Figure 10 based on over than 2,000 analyses with varying length, depth, thickness, radius, and COD values. The presented comparison is, however, limited to a narrow range of small leak rates of 0.35-0.55 gpm.

In summary, the current version of PRO-LOCA 4.0 is based on the SQUIRT 3.0 code for predicting mass leak rates. The code still has some convergence issues for very high leak rates.

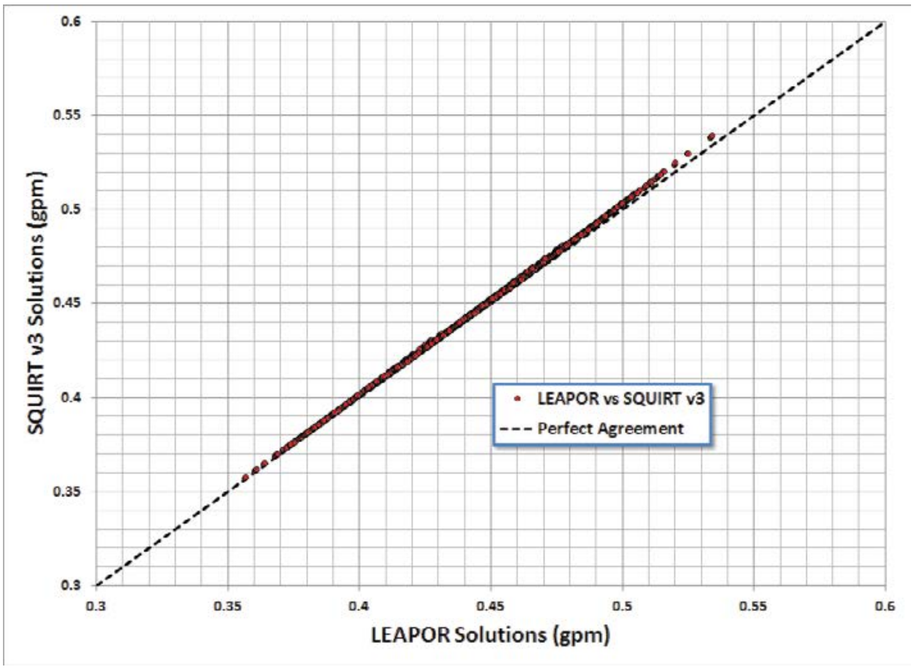


Figure 10 Comparison between modified SQUIRT 3.0 and the new LEAPOR code developed by Oak Ridge National Laboratory.

4 PRO-LOCA Input and output

Section 3 of this report has provided the description of the technical basis of PRO-LOCA, including all main modules called at different stages of a probabilistic analysis. The current section will briefly cover the PRO-LOCA capabilities regarding input of the data required for analysis, interaction with the PRO-LOCA code via a Graphical User Interface (GUI) and output of the results for further post-processing.

At the end of the PARTRIDGE project, Battelle has provided for TAG members the Draft User's Manual [13] along with the latest versions of PRO-LOCA 4.1.9 and the GUI 4.0.4.8. Pre-processing and post-processing details are fully documented in the User Manual. The following sections will only provide a brief overview.

4.1 Input control (GUI pre-processing)

There are two alternative ways to enter input data and create an input file in PRO-LOCA. The input file can be created or modified from the existing files manually, although it can only be recommended for experienced users. A starting part of a PRO-LOCA input file is demonstrated for illustration in Figure 11. Later, the PROLOCA GUI was developed for helping the user expedite the generation of inputfiles. The main window of the PRO-LOCA GUI is shown Figure12.

```
BWR_PLR_300_Mitigation
Uses 3rd order polynomial no fabrication flaws
Cluster numbed is 250
Single Crack Analysis
Uses mitigation
Number_of_simulations
 1       10000
Maximum_Circumferential_cracks        Maximum_Axial_cracks
 1 0
Transition_Flag_0:_Use_idealized_1:_Use_transition_1_COD_Flag_1:Battelle_Model_2:GE_EPRI_Original
 2
IMORPH_:_1_-_User_Input_0_-_Hardwired_deterministic value
 0
ICMORPH_:_Model_Type_if_IMORPH_=_0
 1
Use_UWFM_for_WRS_(0_=_input_coefficients,_1_=_3rd_order_polynomial,_2_=_UWFM_mag
 1
Point_to_point_correlation_for_UWFM_for_WRS
  0.90000
Number_of_fabrication_flaws
 0
Number_of_bins
 0
Use_adaptive_sampling?
 1
Number_of_Cluster_Simulations
 250
Number_of_LHS_Replicates
 0
```

Figure 11 An example of the PRO-LOCA input file.

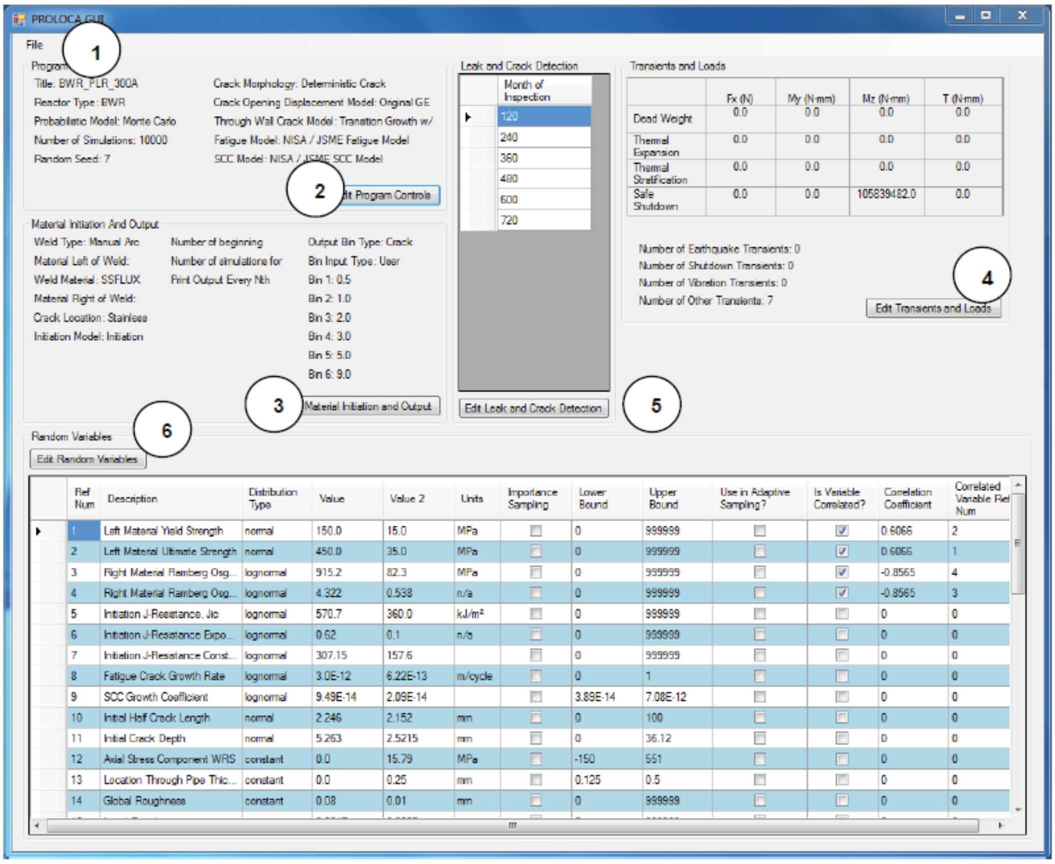


Figure 12 Main window of the PRO-LOCA GUI.

The PRO-LOCA GUI contains six sub-level input blocks (marked by numbers 1-6 in Figure 12) which can be accessed by user. The names of these input blocks are self-explaining and the detailed information regarding the input required in the respective input blocks is given in the User Manual [13]. Therefore, further details on working with the input files via GUI can be found in [13].

One drawback of the current version of GUI can be mentioned here. Even though the GUI provides functionality to save the current state of progress of the GUI (*.pgsf file) and export the finished input deck into the text file, the GUI is currently lacking capability of reading/importing the PRO-LOCA text input files in the format shown in Figure 11.

4.2 Output (Post-processing)

In early versions of PRO-LOCA (up to and including 2.0) the results were output in terms of calculated event probabilities of occurrence of a surface crack initiation, a rupture due to a through-wall crack, and six upper bound bins defined as crack opening areas (COA). The probabilities of occurrence were presented in terms of a threshold COA, i.e., the probability that a crack-opening area greater than a specified value will develop. The six crack-opening areas and associated effective opening diameters (assuming circular openings) are given in Table 2.

Table 2 Definition of crack opening area outputs in PRO-LOCA.

Crack opening area (COA)	**Effective Opening Diameter**	**LOCA Category**
93.5 mm^2 (0.145 $inch^2$)	11 mm (0.43 inch)	1
1,406 mm^2 (2.18 $inch^2$)	42.4 mm (1.67 inch)	2
4,690 mm^2 (7.27 $inch^2$)	77.3 mm (3.04 inch)	3
23,477 mm^2 (36.4 $inch^2$)	173 mm (6.81 inch)	4
100,645 mm^2 (156 $inch^2$)	358 mm (14.1 inch)	5
503,225 mm^2 (780 $inch^2$)	800 mm (31.5 inch)	6

These COAs and effective opening diameters closely correspond with the six LOCA categories used in the expert elicitation study for predicting leakage and rupture frequencies in PWR plants [1]. It can be noted that the development of a through-wall crack (TWC) corresponds to Category 0 LOCA as it was the case during the elicitation. However, the hard-coded COA sizes may also be limiting for PRO-LOCA flexibility when the analyses of smaller or larger piping would be desired. Thus, for analyses of piping with smaller diameter some of the default COA sizes may be larger than the internal opening pipe area, i.e. the double edge guillotine break (DEGB) size, rendering the results beyond the DEGB size as irrelevant.

Under PARTRIDGE program, PRO-LOCA 3.0 and higher versions was enhanced with a capability of having user defined COA sizes in addition to the default sizes in Table 2. If the user defined COA sizes are selected, a user can define the output for the event probabilities in terms of the crack opening area (COA), the equivalent pipe diameter, or the leak rate [13]. However, the results in terms of COA probabilities from two different analyses can directly be compared with each other only for initiation, TWC and rupture curves. The probabilities for COA can be compared only if the COA bin sizes are equally defined.

Three output probabilities are provided for each event (TWC, bins, and rupture). These are probabilities with no detection (from inspections or leak detection), probabilities with crack detection, and probabilities with leakage detection. There is a possibility to choose the combined leakage and crack detection, so then the probability with leakage detection includes the crack detection probabilities. If the user selects the Leakage Detection only, then only the impact from leakage detection is included [13].

Currently PRO-LOCA is lacking post-processing capabilities. The results from analyses are provided in text output files which can be read by Excel or MATLAB for producing plots and post-process the calculation results. This is quite tedious task because of large volume of produced data. It limits the use of PRO-LOCA in industrial environment but is acceptable for now as the code was successively declared as a research code.

5 Benchmark analyses

Several pre-constructed input files were supplied to TAG members for testing and benchmarking of PRO-LOCA 4.0. The input files cover both BWR and PWR plants as well as different piping geometries, materials and degradation mechanisms. In addition to the traditional Monte-Carlo simulation, discrete probability methods including adaptive sampling can be used with PRO-LOCA 4.0. The provided input files were constructed so that all available probabilistic models could be evaluated. A summary of the provided input files for PRO-LOCA 4.0 is given in Table 3.

Table 3 Summary of the test input files for PRO-LOCA analyses.

<table>
<tr><th>File name</th><th>Information</th></tr>
<tr><td>BWR_PLR_300</td><td>• Based on Ref. [31].
• The pipe size, transient stresses, seismic stresses, fatigue and SCC crack growth equations are implemented in the input file from [31].
• Normal operating membrane stress and residual stress distribution from the reference are not considered.</td></tr>
<tr><td>BWR_PLR_300_Mitigation</td><td>• Based on BWR_PLR_300 case above but the pre-emptive mitigation is performed at 59 months of operation.</td></tr>
<tr><td>NURBIM_Large</td><td rowspan="3">• Based on Ref. [32].
• The pipe sizes in input files are based on NURBIM_Large, NURBIM_Medium, and NURBIM_Small cases in [32].
• The crack depth distribution and defect aspect ratio for the crack initiation, loading conditions, material properties, and crack growth law parameters are employed for the Medium case from NURBIM study [32].</td></tr>
<tr><td>NURBIM_Medium</td></tr>
<tr><td>NURBIM_Small</td></tr>
<tr><td>Probabilistic_xLPR</td><td>• Based on xLPR version 1.0 Report-Technical basis and pilot study problem results (February 2011)</td></tr>
<tr><td>PWSCC_Base</td><td>• Based on the reference PWSCC case used during the 1st PARTRIDGE TAG meeting in June 2012.
• Normal operating loads are from the xLPR version 1.0 report.</td></tr>
</table>

In this study, for benchmark and the sensitivity analyses two test cases from Table 3 have been selected. The selection criteria were the following. The cases should be representative for BWR and PWR plants and take into account SCC and fatigue cracking degradation mechanisms. The chosen cases are described in detail below and further analysed using the final release version of PRO-LOCA 4.1.9.

5.1 PWR pipe – PWSCC baseline case

The PWSCC_Base case in Table 3 addresses the Alloy 82/182 dissimilar metal (DM) weld at the pressurizer surge nozzle in PWRs. This case was previously analysed with earlier version of PRO-LOCA 3.0 in the beginning of the PARTRIDGE program and therefore, is well documented. In addition, the benchmark and sensitivity analyses for the PWSCC_Base case were performed by Korean consortium using the PRO-LOCA 4.0 code as a part of the work in PARTRDIGE program [9].

The probabilistic model used for the PWSCC baseline case was the traditional Monte Carlo (MC) method with 10^4 iterations. It was assumed that no fabrication flaws existed in the weld of the pressurizer surge nozzle but one in-service crack was initiated in the weld material. The user defined crack initiation model was chosen with distributed time parameter for crack initiation, and log-normal distribution for crack depth and length parameters. PWSCC cracking was assumed as the primary degradation mechanism. Fatigue cracking was excluded as it provides negligible contribution in comparison to PWSCC. The new PWSCC growth model from xLPR 1.0 was used in analysis of the baseline case.

The weld residual stresses are defined using the Universal Weight Function Method (UWFM) as described in Section 3.10. The WRS variation through the pipe wall is depicted in Figure 13. The current version of PROLOCA allows for simulating a pre-emptive mitigation of tensile residual stresses at the pipe ID by modifying the weld residual stress distribution. In this case, the same user defined UWFM WRS model is used with the modified (mitigated) WRS distribution. The effect of WRS mitigation is shown in Figure 13 and will be assessed in the sensitivity analyses in the next Section.

An inspection interval of 6 years was deterministically defined in the baseline case. The baseline POD function used for crack detection is shown in Figure 14. We note that this POD curve represents a rather pessimistic detection capability as a crack with depth of 32 mm (about 80% of the pipe wall) can be detected with POD = 0.8. Therefore, in the sensitivity analyses a rather optimistic (advanced) POD curve (also depicted in Figure 14) is employed to investigate the potential reduction of rupture probabilities.

In general, most of the parameters for the PWSCC baseline case were considered as distributed variables in order to account for uncertainty effects. The most essential input parameters are summarised in Table 4. We note that in this benchmark case a very high uncertainty was assumed for the fracture toughness as the standard deviation is large.

Table 4 Parameters for the PWSCC baseline case.

Parameter	Value Mean value (std. dev.)	Distribution type Comment
Sampling method	Monte Carlo	-
Number of iterations	10,000	-
Number of fabrication cracks	0	-
Number initiated cracks	1	Initiation model with distributed initiation time, crack length and depth-
Initial crack depth [mm]	1.5 (0.075)	Log-normal
Initial half crack length [mm]	3 (0.15)	Log-normal
Pipe pressure [MPa]	15.51 (0.155)	Normal
Temperature [℃]	315 (0.1)	Normal
Pipe diameter, wall thickness [mm]	381, 40.13	Constant
Young's Modulus [GPa] SS/CS	177.1 (21.4) / 186.3 (16.7)	Normal
Yield Strength [MPa] SS/CS	168.7 (36.5) / 228.5 (27.7)	Log-normal
Ultimate Strength [MPa] SS/CS	450.6 (53.2) / 519.9 (33.7)	Log-normal
Ramberg-Osgood, n $[-]$ SS/CS	4.29 (0.57) / 4.26 (0.53)	Log-normal
Ramberg-Osgood, F $[-]$ SS/CS	563.8 (43.6) / 562.1 (82.3)	Log-normal
Fracture toughness, J_{Ic} $[\mathrm{kJ/m^2}]$	482.7 (360)	Log-normal
J-R curve, C [-]	260.1 (157.6)	Log-normal
J-R curve, m $[-]$	0.612 (0.1)	Log-normal
SCC crack growth coefficient [m/s]	$9.83 \cdot 10^{-13}$ $(1.52 \cdot 10^{-14})$	Log-normal
Exponent for SCC growth, m $[-]$	1.6	Constant
WRS distribution	UWFM	-
Leak rate detection [gpm]	5 (0.5)	Normal
Inspection interval [years]	6	Constant

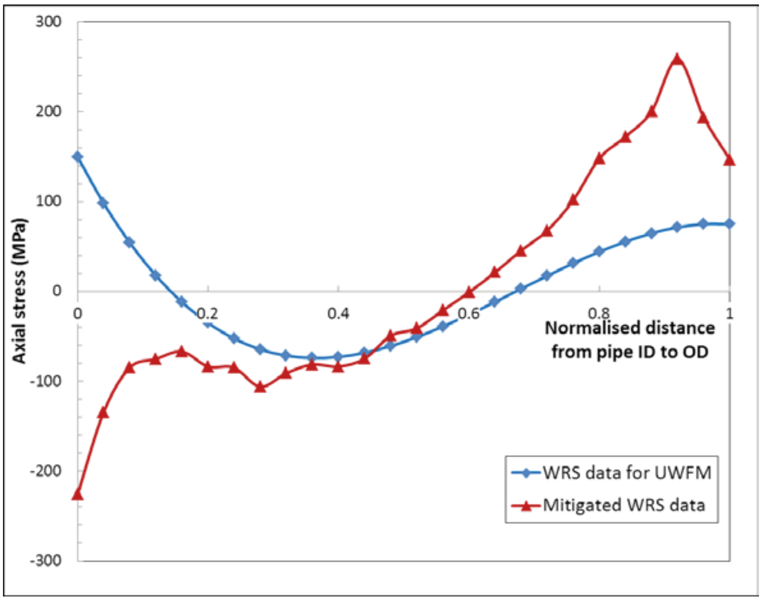


Figure 13 Distribution of weld residual stresses through the pipe wall for the UWFM method.

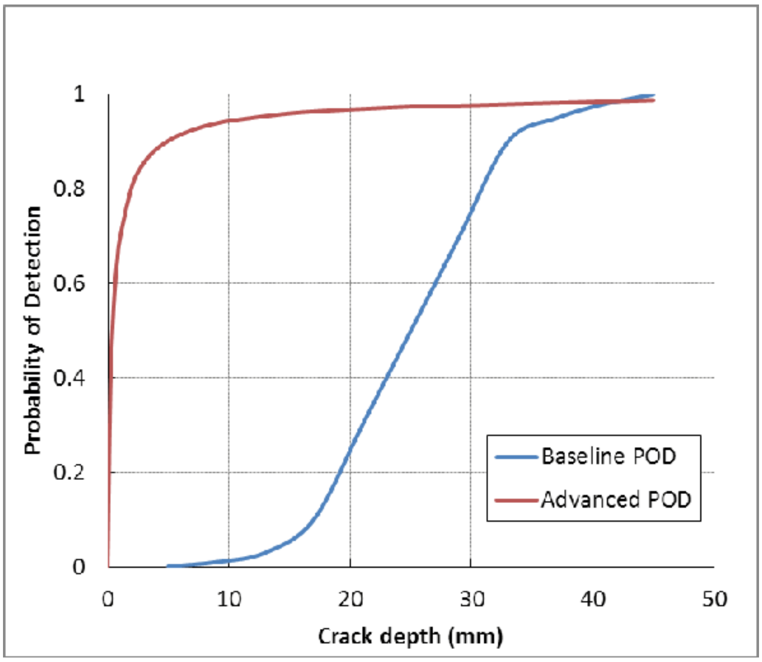


Figure 14 The probability of detection curve as a function of crack depth.

Typical results from PRO-LOCA analysis are presented below. The probabilities for leakage due to occurrence of a through-wall crack (TWC) and pipe rupture are plotted as function of operation time of 60 years in Figure 15. The effect of crack detection by NDE methods using the baseline POD function from Figure 14 on the probabilities for TWC leak and pipe rupture is also demonstrated in Figure 15. The accumulated leak and rupture probability at 60 years with crack detection are about one magnitude lower in comparison with 'no inspection' values.

a)

b)

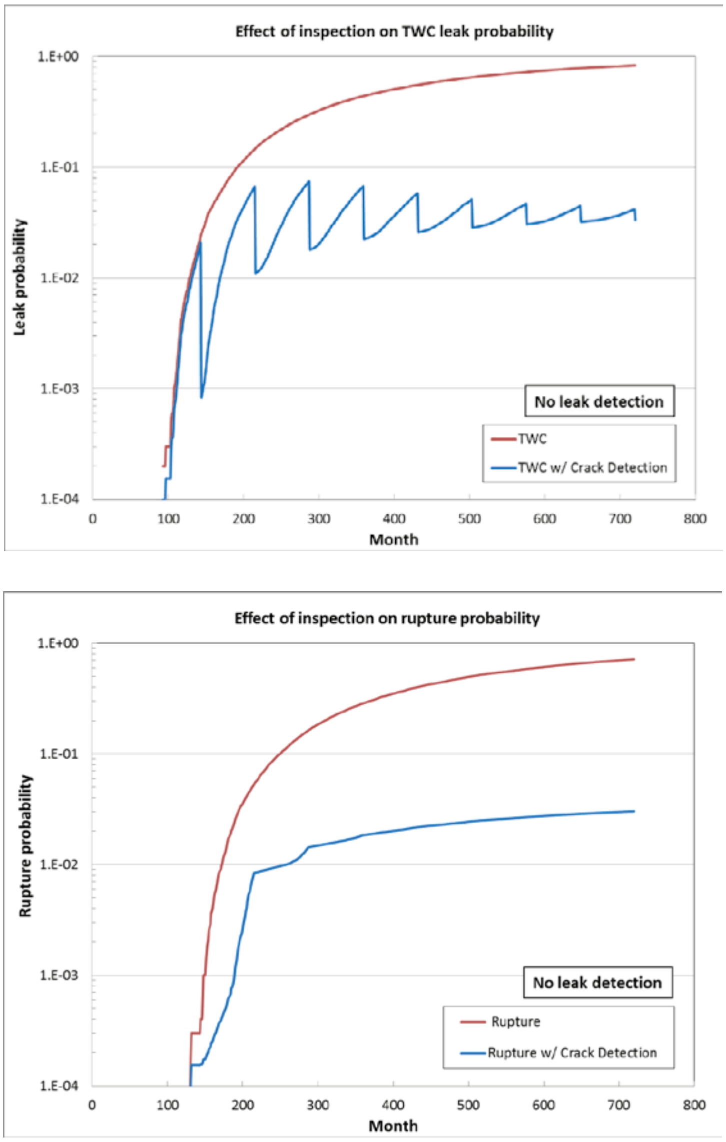


Figure 15 TWC leakage and pipe rupture probabilities for the PWSCC baseline case.

The baseline analysis was performed using 10^4 MC simulations. In order to investigate if the number of simulations is sufficient for ensuring convergence, the PRO-LOCA analysis with 10^5 MC was performed. The PRO-LOCA results are compared in Figure 16 demonstrating that the calculated probabilities are almost identical.

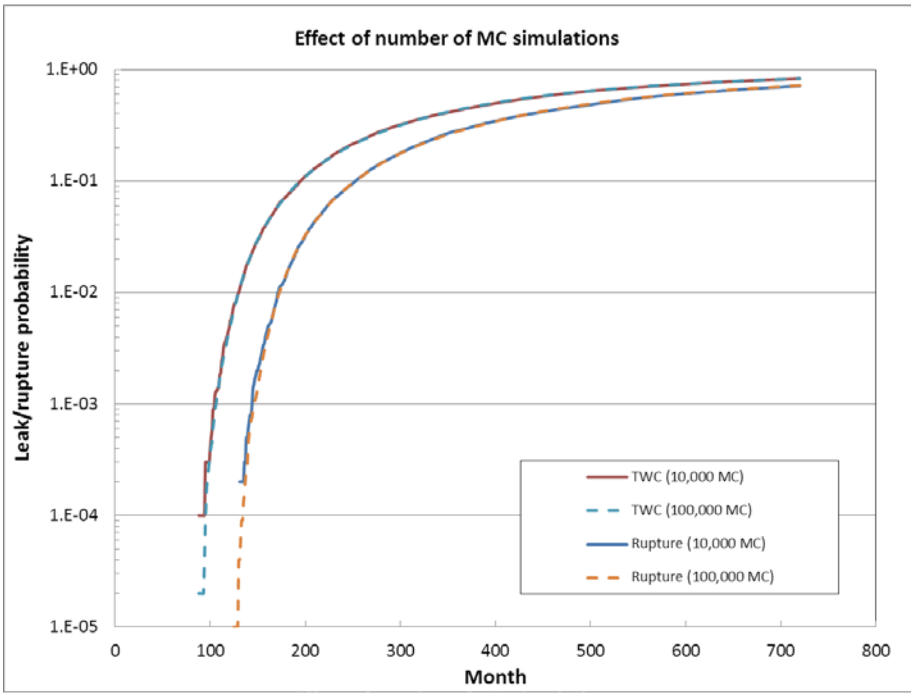


Figure 16 Calculated probabilities for TWC leak and pipe rupture for PWSCC baseline case. The results are from analyses with 10,000 and 100,000 Monte Carlo simulations.

5.2 BWR pipe – Fatigue baseline case

As part of the international project NURBIM (Nuclear risk-based inspection methodology for passive components), the fatigue benchmark study of different PFM codes was previously conducted for three geometries denoted as Large, Medium, and Small piping [32]. In the PARTRIDGE program, for benchmarking of the PRO-LOCA code with respect to fatigue degradation mechanism, three input files were provided based on the NURBIM pipe cases (see Table 3).

As the baseline case in this report, the NURBIM_Medium stainless pipe was chosen for benchmark analysis. Most of the input parameters for the PRO-LOCA input file were directly taken from Ref. [32], e.g. the crack depth distribution and defect aspect ratio for the initiated crack, loading conditions, material properties, and fatigue crack growth (FCG) law parameters. Almost all parameters in PRO-LOCA may be defined as distributed variables in order to account for uncertainty effects. Here for achieving a close resemblance with the NURBIM cases, only few input parameters for the baseline case were considered as distributed variables. The input parameters for the NURBIM fatigue baseline case are summarised in Table 5.

The probabilistic model used for the NURBIM fatigue baseline case was the traditional Monte Carlo (MC) method with 10^4 iterations. It was assumed that no fabrication flaws exist in the weld. A single in-service crack was initiated in the weld material using the user defined crack initiation model with log-normal distribution for initial crack depth and deterministic (constant) initial defect aspect ratio.

Table 5 Parameters for the NURBIM Medium fatigue baseline case.

Parameter	**Value** **Mean value (std. dev.)**	**Distribution type**
Sampling method	Monte Carlo	-
Number of iterations	10,000	-
Number of fabrication cracks	0	-
Number initiated cracks	1	-
Initial crack depth [mm]	2.752 (2.071)	Log-normal
Initial defect aspect ratio (half-length/depth)	3	Constant
Pipe pressure [MPa]	15.4	Constant
Temperature [°C]	315	Constant
Diameter [mm]	324	Constant
Thickness [mm]	33.3	Constant
Young's Modulus [GPa]	180	Constant
Yield Strength [MPa]	150 (15.0)	Normal
Ultimate Strength [MPa]	450 (35.0)	Normal
Ramberg-Osgood, n $[-]$	4.33 (0.57)	Log-normal
Ramberg-Osgood, F $[-]$	565.48 (43.6)	Log-normal
Fracture Toughness, J_{Ic} $[\mathrm{kJ/m^2}]$	356.9 (27.03)	Normal
Fatigue crack growth model	Paris law model	-
Fatigue crack growth coefficient [m/cycle]	$5.06 \cdot 10^{-12}$	Constant
Exponent for fatigue crack growth m $[-]$	3.93	Constant
Leak rate detection [gpm]	1 (0.1)	Normal
Inspection interval [years]	6	Constant

Typical results from PRO-LOCA analysis for the NURBIM fatigue baseline case are presented below. The probabilities for leakage due to occurrence of a through-wall crack (TWC) and pipe rupture are plotted as function of operation time of 60 years in Figure 17.

The baseline case was also analysed using 10^5 MC simulations for investigating if the number of iterations is sufficient for convergence. The PRO-LOCA results are compared in Figure 17 demonstrating that the calculated probabilities are almost identical.

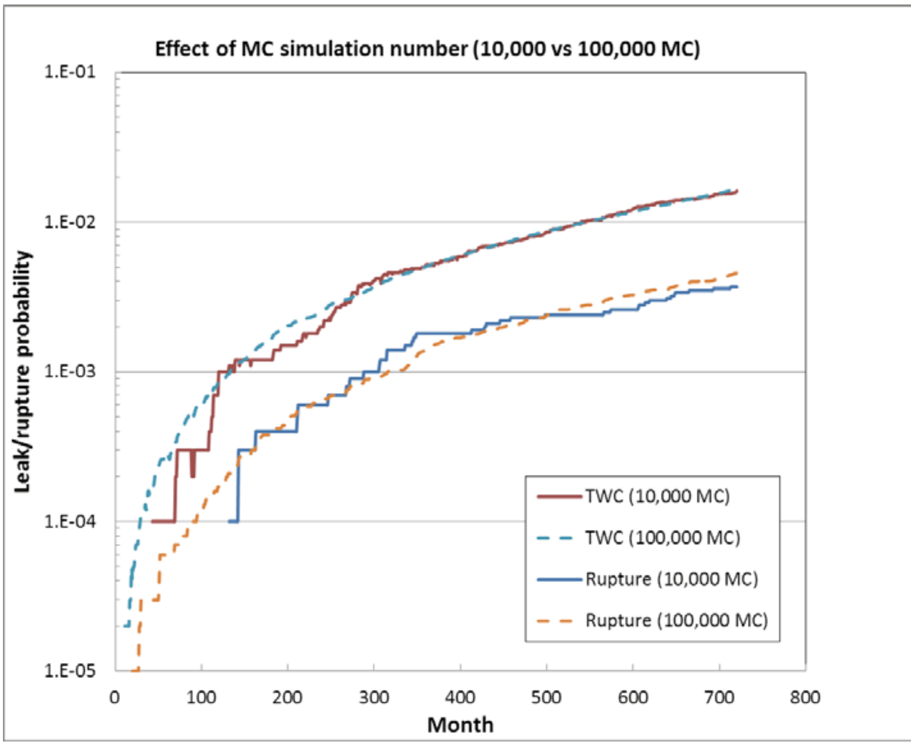


Figure 17 Calculated probabilities for TWC leak and pipe rupture for the NURBIM_Medium baseline case. The results are from analyses with 10,000 and 100,000 MC simulations.

6 Sensitivity Analyses

A general behaviour of the PRO-LOCA code was assessed through the benchmark analyses of two baseline cases in the previous section. Based on these baseline cases a number of sensitivity analyses are performed in this section in order to investigate adequacy of calculated trends.

The sensitivity analyses are performed for a set of selected input parameters which are expected to influence the probability for leak and/or rupture in the piping system in certain way. In sensitivity analyses each input parameter has been varied separately while keeping all other parameters fixed at their baseline values. However, in many cases the sensitivity analyses have been performed with no inspection and no leak detection in order to obtain meaningful (non-zero) results. The input parameters in the baseline cases mostly correspond to the best estimate values reflecting actual conditions of a typical plant. Variation of the input parameters from the best estimate values was generally intended to cover lower and upper bound values.

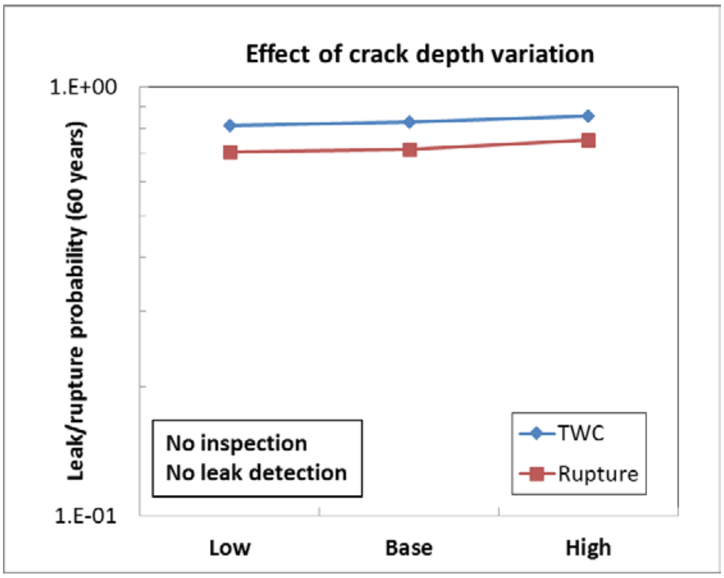
6.1 PWR PWSCC case

The input parameters chosen for the sensitivity analyses of the PWSCC baseline case are given in Table 6. In addition, the sensitivity analyses include the variation of leak detection limit, inspection interval and weld residual stresses in order to evaluate the effect of pre-emptive WRS mitigation according to Figure 13. Also, the effect of employing a more advanced POD curve for crack inspection is considered in the sensitivity study. These four variations are included in Table 6 but marked with grey colour as notations Low, Base and High are not really applicable for these analyses. For the cases where the leak detection limit and inspection interval are investigated, the comparison with the situation of "no leak detection" and "no inspection" is made.

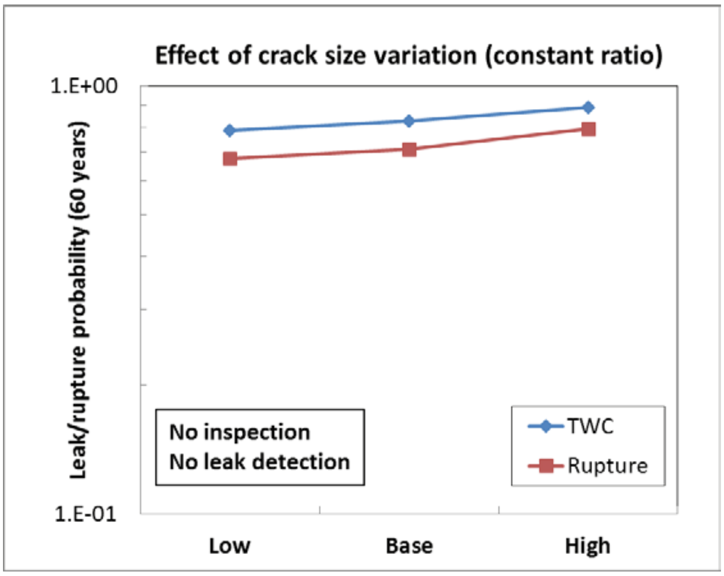
Table 6 Parameters for sensitivity analyses for PWR PWSCC case.

Property	Distribution type	Low		Base		High	
		Mean	STD	Mean	STD	Mean	STD
Crack depth (mm)	Log-normal	0.3	0.015	1.5	0.075	7.5	0.375
Crack half-length (mm)	Log-normal	0.6	0.030	3	0.15	15	0.75
J resistance $(\mathrm{kJ/m^2})$	Log-normal	321.3	240	482.7	360	723	240
Power-law coeff. $\alpha\ (\mathrm{m/s})(\mathrm{MPa}\sqrt{\mathrm{m}})^{\beta}$	Log-normal	$5.0 \cdot 10^{-13}$	$5.0 \cdot 10^{-14}$	$9.83 \cdot 10^{-13}$	$1.52 \cdot 10^{-14}$	$5.0 \cdot 10^{-12}$	$5.0 \cdot 10^{-13}$
Leak detection limit	Normal	0.5	0.05	5	0.5	500	50
Inspection interval	Constant	3	-	6	-	10	-
WRS mitigation	-	-	-	Base WRS	-	Mitig. WRS	-
POD function	-	-		Base POD		Adv. POD	

Results from the sensitivity analyses for the Low, Base and High cases are presented as function of accumulated probability after 60 years in Figure 18 and Figure 19. Variation of the crack depth and crack size under fixed length/depth ratio provides insignificant influence on the calculated probabilities for occurrence of the TWC leak and pipe rupture as shown in Figure 18. The probability values slightly increase for larger depth and size of the initial crack but in general, the values are of the same order of magnitude. This trend may be considered surprising as the flaw size is expected to provide influence on the probability of leak and rupture. A rationale behind this trend can be coupled to high values of calculated probabilities which are close to 1 both for the TWC leak and pipe rupture. It suggests that the PWSCC crack growth rate is very high, thereby extinguishing to a large extent the effect of crack depth and size variation.



a)



b)

Figure 18 PWR PWSCC case: Variation of crack depth and crack size assuming the constant length/depth ratio.

Variation of the fracture toughness values in the range specified in

Table 6 demonstrated a complete insensitivity on the calculated probabilities for occurrence of the TWC leak and pipe rupture as shown in Figure 19 (a). Even though a weak influence of fracture toughness was anticipated, the observed trend, in general, is in agreement with previous sensitivity studies, e.g. NURBIM benchmark study for SCC [33], where the effect of fracture toughness variation was investigated by other PFM codes. In the NURBIM study [33] the change in fracture toughness had a weak effect on the predicted rupture probabilities. Higher values of fracture toughness lead to greater critical crack size and consequently greater times to rupture which reduces the rupture probabilities. At very low fracture toughness values a transition to significantly higher rupture probabilities has been observed. However, this range of fracture toughness values is not covered by current sensitivity analyses with PRO-LOCA.

In PRO-LOCA fracture toughness is only used by the crack stability model. Fracture toughness has a negligible effect on stability of surface cracks which are mainly controlled by limit load. TWC crack stability is calculated by the TWC_Fail model indicating that a critical TWC size is governed by fracture toughness in most cases. Thus, higher fracture toughness should also provide greater critical crack size and contribute to lower rupture probabilities predicted by PRO-LOCA. However, insignificant effect of fracture toughness suggests that it is not a major driver. The values of calculated probabilities are very high (almost equal to 1) indicating that crack growth rate may have much stronger effect thereby extinguishing an expected weak influence of fracture toughness.

A more pronounced effect on the calculated probabilities was found for variation of the power-law coefficient for the PWSCC xLPR1.0 model as shown in Figure 19 (b). The probability values are still within the same order of magnitude but a decrease in the PWSCC growth rate provided lower probabilities. The difference between the probability for TWC leak and pipe rupture also increases with decreasing the SCC growth rate as can be seen for the case ‘Low’ in in Figure 19 (b).

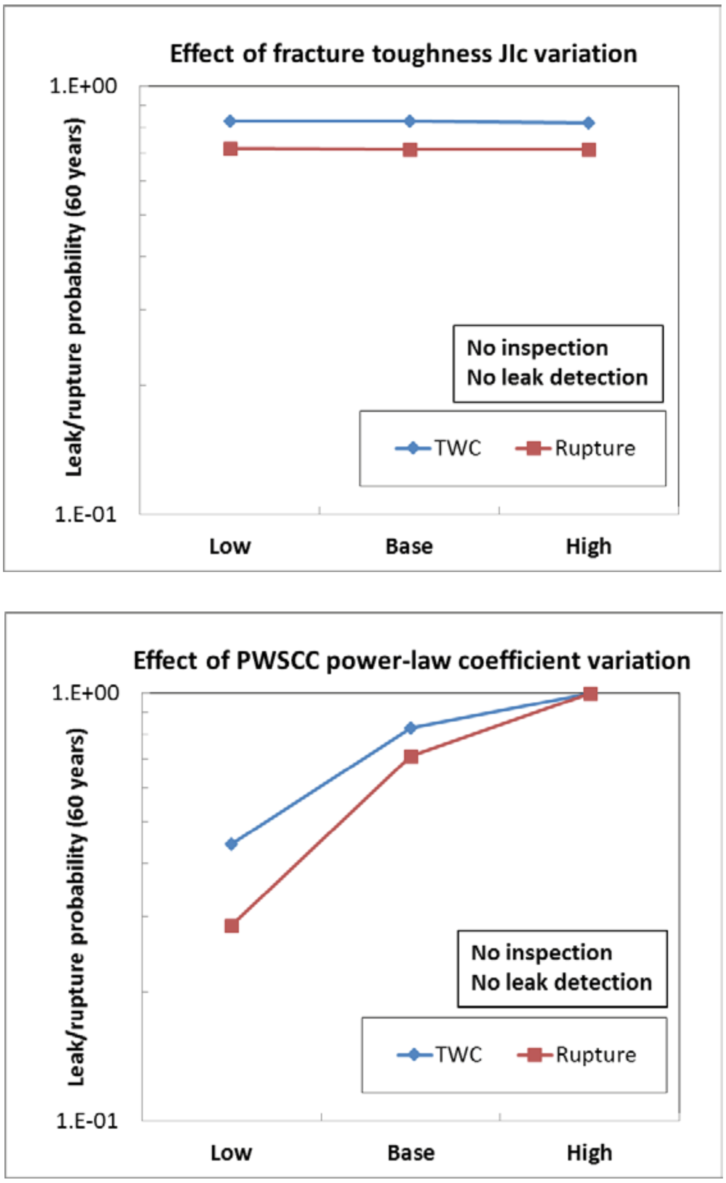
a)
b)


Figure 19 PWR PWSCC case: Variation of fracture toughness $\mathbf{J_{Ic}}$ and the PWSCC growth constant C.

An effect of inspection interval is investigated by considering the interval of 3, 6 and 10 years in comparison to "no inspection" case. The results for calculated probabilities for the occurrence of the TWC leak and pipe rupture taking into account the crack detection are shown in Figure 20 (a). Shorter inspection interval demonstrates a significant reduction in the leak/rupture probability values of almost two magnitudes between "no inspection" and 3 years, and about one order of magnitude when 10 years inspection is considered.

The results for leak detection capability are presented in Figure 20 (b). The leak rate binning system was used in the analyses and the effect of leak detection limit is demonstrated for the output bin 3 (leak rate of 10 gpm). The effect of leak detection is investigated for leak detection limits of 500, 50, 5 (baseline) and 0.5 gpm which represent a range of leak detection capabilities starting from a poor (500 gpm) to very sensitive (0.5 gpm). The results are compared with “no leak detection” case.

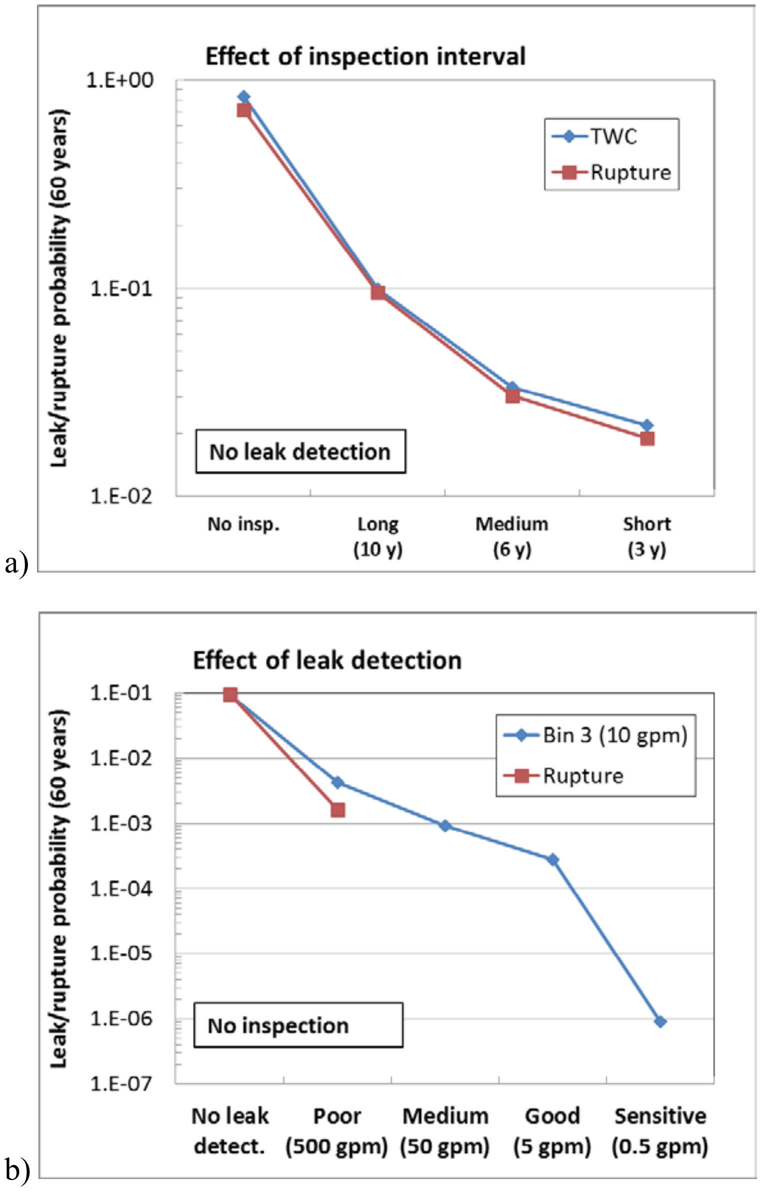


Figure 20 PWR PWSCC case: Variation of inspection interval and leak detection limit.

The predicted leak probabilities decrease by 5 orders of magnitude from “no leak detection” to 0.5 gpm (sensitive system) as can be seen for the Bin 3 results in Figure 20 (b). For the rupture case the probabilities were zero for the leak detection limit of 0.5 gpm, 5 gpm and 50 gpm which indicated that the cracks are being detected and removed before they could ever grow to a rupture condition. For the larger leak detection limit of 500 gpm PRO-LOCA calculated non-zero rupture probabilities of about two orders of magnitude lower in comparison to “no leak detection” case as shown in Figure 20 (b).

As part of the sensitivity study, the probabilities for occurrence of TWC leak and pipe rupture were compared for the baseline WRS and mitigated WRS distributions through the pipe wall as shown in Figure 13. It was assumed in the analyses that WRS mitigation occurs after 10 years of plant operation. A considerable reduction in the probability values was obtained for the case of mitigated WRS as shown in Figure 21.

The mitigation of weld residual stresses can provide a few orders of magnitude reduction in the calculated probabilities.

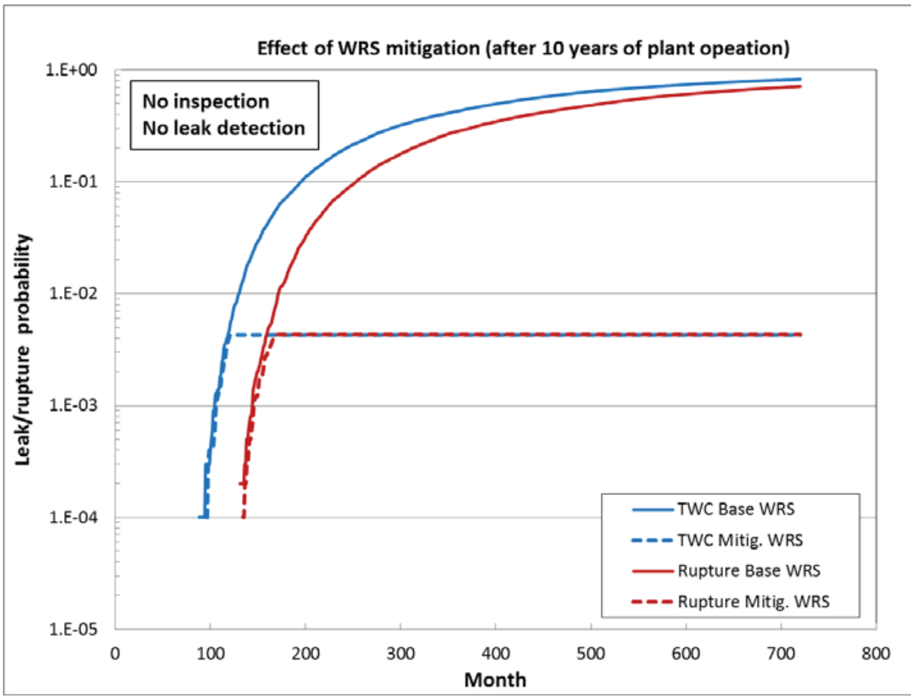


Figure 21 PWR PWSCC case: Effect of WRS mitigation after 10 years of plant operation on probabilities for TWC leak and pipe rupture.

As mentioned previously, the POD curve for crack detection in the PWSCC baseline case was considered to correspond to a poor (rather pessimistic) NDT method as the cracks with depth of 80% of the pipe wall are to be detected with probability of 0.8 (see Figure 14). Therefore, as part of the sensitivity study, a more advanced POD curve was considered in the baseline case.

A comparison of predicted probabilities for TWC leak and pipe rupture is presented in Figure 22 assuming 10 year inspection interval. By employing an NDT system with better POD function provides a reduction in the probability values of about one magnitude in comparison with the poor POD function.

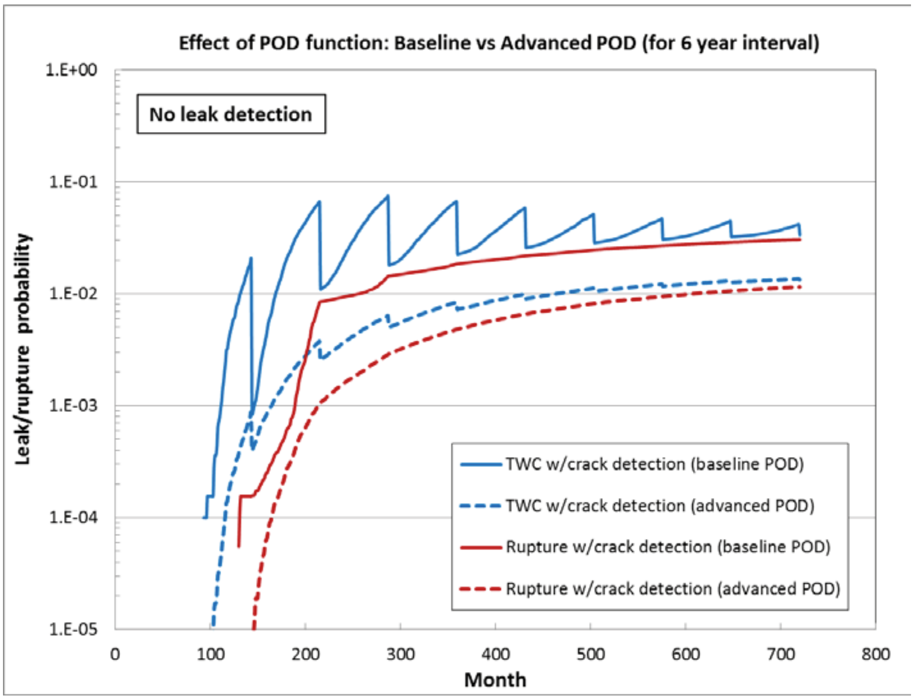


Figure 22 PWR PWSCC case: Effect of using advanced POD function in crack detection on the calculated probabilities for TWC leak and pipe rupture.

For summary, the PWSCC degradation mechanism in the considered case can be effectively managed by selection of appropriate inspection interval, suitable NDT method which provides reasonable probability of crack detection capability and measures for mitigating of weld residual stresses.

6.2 BWR Fatigue case

The input parameters chosen for the sensitivity analyses of the NURBIM_Medium baseline case are given in Table 7. In addition, the sensitivity analyses include the variation of leak detection limit and inspection interval. These variations are included in Table 7 but marked with grey colour as notations Low, Base and High are not really applicable for these analyses. For the case where the inspection interval is investigated, the comparison with the situation "no inspection" is made.

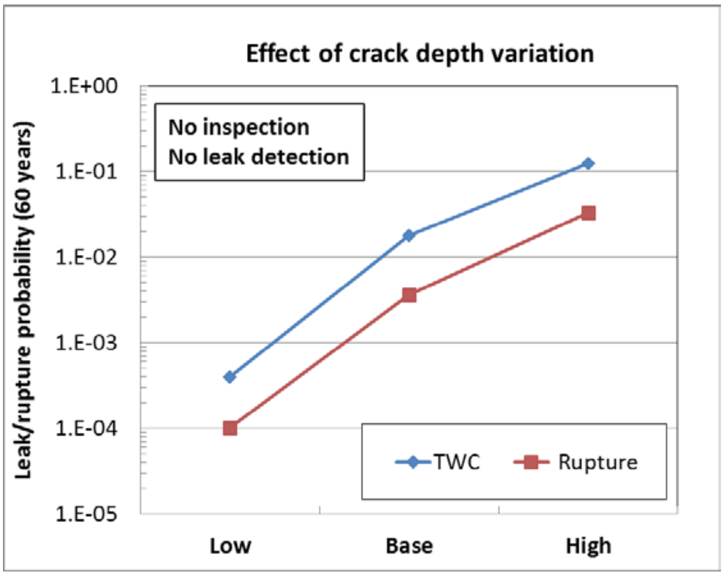
The sensitivity analyses results are presented as function of accumulated probability after 60 years in Figures 23-26.

Table 7 Parameters for sensitivity analyses for NURBIM Medium case.

Property	**Distribution type**	**Low**		**Base**		**High**	
		Mean	STD	Mean	STD	Mean	STD
Crack depth (mm)	Log-normal	1.35	1.016	2.752	2.071	5.5	4.139
Defect aspect ratio	Constant	1	-	3	-	10	-
Yield (MPa)	Normal	75	7.5	150	15	225	22.5
Ult. strength (MPa)	Normal	225	15	450	35	675	45
J resistance (kJ/m^2)	Normal	99.9	7.68	356.9	27.03	999.7	75.70
FCG law C ($m/cycle$)	Constant	$1.0 \cdot 10^{-12}$	-	$5.06 \cdot 10^{-12}$	-	$1.0 \cdot 10^{-11}$	-
Leak detection limit	Normal	0.1	0.01	1	0.1	10	1
Inspection interval	Constant	3		6		10	

Variation of the crack depth and crack aspect ratio provides a significant influence on the calculated probabilities for occurrence of the TWC leak and pipe rupture as shown in Figure 23. The probability values differ by two orders of magnitude between the Low and High cases. Similar trends were observed in the fatigue benchmark study in NURBIM project [32]. However, the absolute values of calculated probabilities obtained by other PFM codes were lower in Ref. [32].

a)



b)

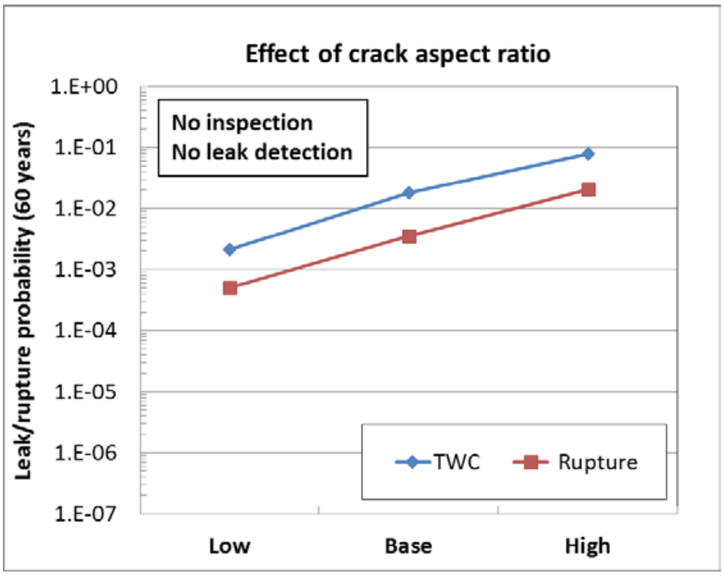


Figure 23 BWR NURBIM fatigue case: Variation of crack depth and crack aspect ratio.

Variation of yield stress exhibited a very weak effect on the calculated probabilities for TWC leak and pipe rupture as shown in Figure 24 (a). Variation of ultimate tensile strength provided no effect on the calculated TWC probability but gave a certain influence on the calculated rupture probability as shown in Figure 24 (b). This trend is the opposite to what is expected. Changes in the yield stress or ultimate tensile strength result in changes of flow stress which controls net section collapse. A decreased flow stress should lead to higher rupture probability and vice versa. In NURBIM project [32] it was demonstrated that rupture probability was relatively insensitive to a range of flow stress values followed by quite sharp transition to higher probabilities when the flow stress approached the primary stress levels. The trend from Figure 24 (b) where the rupture probability increased with increased ultimate tensile strength is unexpected and should be investigated further.

Variation of fracture toughness is investigated in Figure 25 (a). For lower values of fracture toughness the maximum allowable stress intensity factor along the crack front is also reduced. Therefore, it is reasonable to anticipate that the decreased fracture toughness values should provide a higher leak and rupture probabilities.

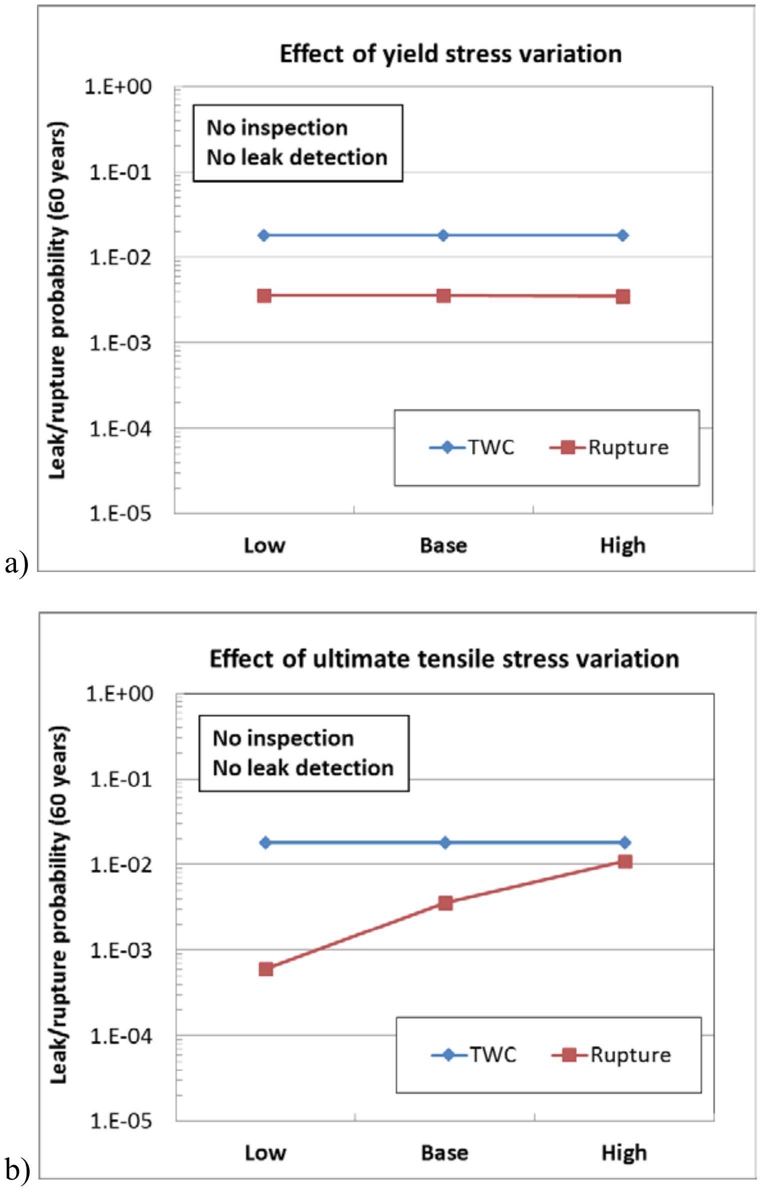
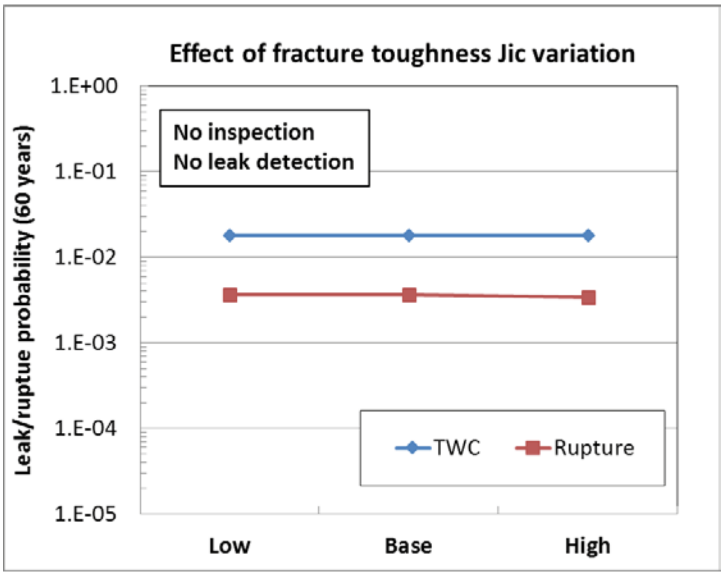


Figure 24 BWR NURBIM fatigue case: Variation of yield stress and ultimate tensile strength.

In NURBIM fatigue benchmark study [32] it was also argued that a change of fracture toughness has a very weak influence on the probability values because the stress intensity factor for most of the evaluated cracks are below the fracture toughness of the material. To confirm this rationale, the additional analyses with even lower fracture toughness values were conducted under NURBIM study and demonstrated the effect of increasing probabilities for very brittle material.

a) 

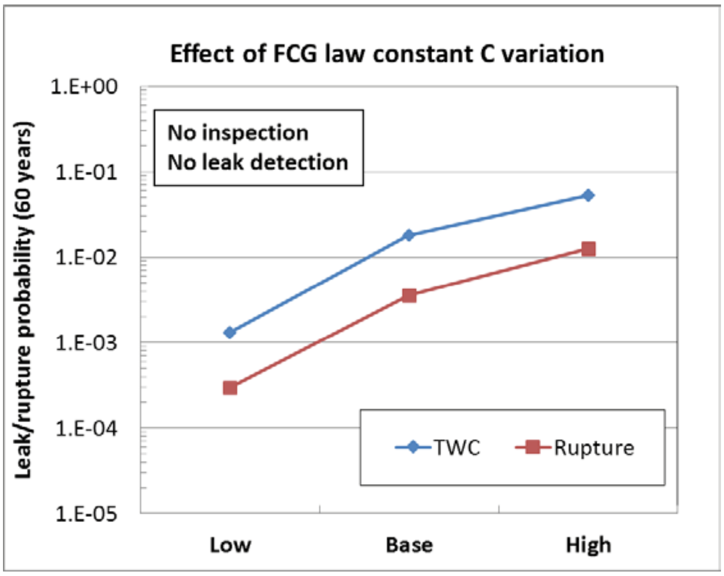
b) 

Figure 25 BWR NURBIM fatigue case: Variation of fracture toughness and FCG law constant C.

As expected, the variation of the FCG law constant exhibited a noticeable effect on the calculated probabilities as shown in Figure 25 (b). The FCG law constant was varied by one order of magnitude between the Low and High cases providing a change in TWC leak probabilities of about two orders of magnitude. The observed trend is consistent with the trends from Ref. [32].

An effect of inspection interval for the NURBIM Medium case is investigated by considering the interval of 3, 6 and 10 years and comparing with "no inspection" case. The results for calculated probabilities for occurrence of the TWC leak and pipe rupture taking into account the crack detection are shown in Figure 26. Probability values for the occurrence of TWC and rupture demonstrate a substantial decrease by 2 orders of magnitude between the "no inspection" situation and long inspection interval (10 years). Reducing the inspection interval from 10 to 3 years demonstrate a further decrease in probabilities of about 1 order of magnitude.

Also, it was an intention to investigate a variation of leak detection limit on probability values for NURBIM_Medium case. However, these analyses were unsuccessful as PRO-LOCA produced zero rupture probabilities for all leak detection limits between 0.1 and 10 gpm. This indicates that for these leak detection limits, all leaking cracks will be detected by leak detection before rupture and will thus not contribute to the rupture probability.

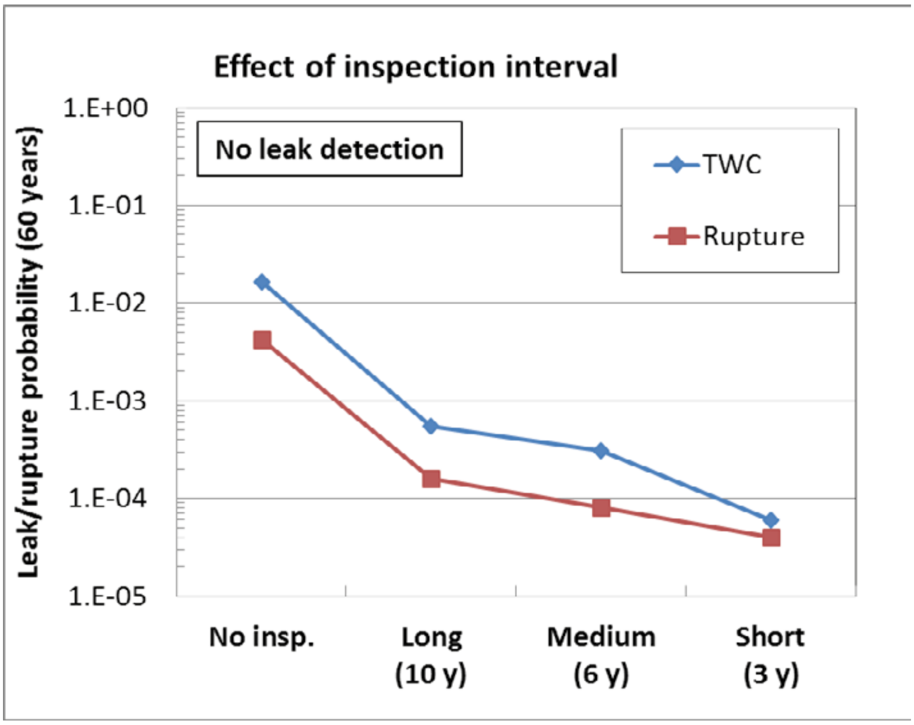


Figure 26 BWR NURBIM fatigue case: The effect of inspection interval on predicted probabilities.

7 Probabilistic integrity assessments in Sweden

Relevance and importance of probabilistic assessments of structural integrity for Swedish nuclear industry are discussed below considering different aspects;

1. Current regulatory requirements and application of probabilistic methods to address today's challenges in structural integrity;
2. New challenges related to safety concerns, environment and economy that may arise under long term operation (LTO) of aged reactors;
3. New SSM requirements that may be introduced in regulatory documents according to recently published SSM perspective [34][35].

7.1 Current regulatory requirements and application of PFM methods

Application of probabilistic fracture mechanics (PFM) methods and approaches is currently allowed by SSM regulations and guidelines in several situations as a complement to deterministic analyses for demonstrating compliance to regulatory requirements.

According to 12 § requirement in SSM 2008:17 a nuclear power reactor shall withstand global and local loads arising in consequence of a postulated pipe break which may jeopardise the safety barriers and safety functions. Local dynamic effects can, according to 13 § SSM 2008:17, be excluded in the piping systems where measures have been taken so that damage due to known or potential degradation mechanism will lead to detectable leakage before a pipe break occurs.

SSM report [36] provides guidance on how compliance with these requirements can be demonstrated. It describes the locations where pipe breaks should be postulated and how the consequence of postulated pipe breaks should be assessed against acceptance criteria. According to 3 § SSM 2008:17 a pipe break and its direct consequence is acceptable, if prescribed safety functions are maintained and can tolerate a single failure. If compliance with the acceptance criteria cannot be shown, physical protection measures (e.g. pipe whip restraints, etc.) for mitigating consequence of the pipe break should be considered. However, in certain situations where physical protection is not possible or feasible, the probabilistic analyses can be used for demonstrating that the pipe break probability is very low and can be considered as a residual risk. Also, the probabilistic analyses may quantitatively demonstrate low probability of a pipe break and existence of a sufficient margin between detectable leakage and pipe break thereby complementing the deterministic LBB-assessment for compliance with 13 § SSM 2008:17 requirement.

Another important application of probabilistic methods is for risk-informed in-service inspection (RI-ISI), chapter 3 in SSM 2008:13. Quantitative assessments of leak and pipe rupture probabilities can provide support for determination of inspection intervals and selection in RI-ISI strategies.

When degradation or damage is detected at recurrent inspections, at maintenance work or during operation, important steps are to identify the root cause and to perform safety assessments, SSMFS 2008:13, Chapter 2, 6 §. Safety margins are primarily evaluated against general deterministic requirements, in order to determine the acceptable period of operation with damage or defect. This may give a longer period for preparation of repair or other measures. In these cases probabilistic integrity analyses may provide very valuable and detailed information on the driving uncertainties and their influence on safety in the specific situation. Partial safety factors may be investigated by probabilistic analyses and guide the importance of knowledge to reduce uncertainty with respect to each influencing parameter.

7.2 New challenges related to LTO and future regulatory requirements

The Swedish nuclear industry is facing new challenges that may require an increased use of the PFM methods due to;

- Ageing and service-induced damage of safety-related components and systems where it may become increasingly difficult to demonstrate sufficient safety margins by deterministic analyses. Probabilistic results provide more detailed information by quantifying influence of uncertainties in different parameters for the specific situation;
- Regulatory requirements to demonstrate the structural integrity of a reactor pressure vessel (RPV) against neutron embrittlement by both deterministic and probabilistic analyses for Long Term Operation (LTO). The probabilistic analysis should confirm that the RPV failure frequency provides a negligible contribution to the total core damage frequency (CDF) of the plant [35];
- Commitments of the nuclear industry to follow and account for the latest research and technology advancements as a part of the Periodic Safety Review (PSR) work.

Further, new regulations for analysis of radiation safety of nuclear power plants are under development in Sweden, adopting a wider use of the probabilistic approach for regulatory decisions [35]. Currently pipe breaks should be postulated as design basis accidents in systems which may affect the core cooling and reactor isolation. The new regulation may allow for re-categorising such pipe breaks as design extension conditions, if the occurrence frequency for a pipe break can be shown to be lower than 10^{-6} per year.

Development of regulatory strategies and processes which include risk informed approaches has been highlighted by SSM as one of the focus areas in nuclear safety for near– and mid–term perspective [34]. SSM is, for example, looking at possibility for risk-informed LBB-concept where the effects of more advanced NDE or leak detection can be quantified for risk-informed decision guidance. Also, a probabilistic LBB-concept is discussed which may be applied to the piping with active degradation mechanisms together with mitigating actions [35].

Development of probabilistic tools and risk-informed approaches is also on-going activity in other countries. Thus, NRC and the U.S. nuclear industry are currently developing probabilistic approaches and PFM codes in order to address the safety significance of emerging hazards, which previously were unknown or judged insignificant. Several relevant applications of probabilistic approaches have recently been presented by EPRI [37]. For example, the PFM code FAVOR has been used to quantify uncertainty and assess the risk impact associated with potentially non-conservative estimation of fracture toughness values for the RPV steels from older plants.

Another application is the development of the xLPR code, intended to demonstrate compliance with 10CFR50 Appendix A. Dynamic effects associated with postulated ruptures of primary piping systems may be excluded even in the case of piping systems with active degradation mechanisms, provided that extremely low probability of rupture can be demonstrated and assured.

7.3 Swedish R&D advancements in the PFM field

Swedish nuclear industry and regulatory body have for a long time recognised the importance of probabilistic methods. Already in 1990 initial investigations and modelling of pipe failure frequencies due to IGSCC were performed [38]. The first Swedish regulation that required risk-informed inspections was presented in 1994 (SKIFS 1994:1).

Both the industry and the SSM have actively participated and financially supported several R&D projects on probabilistic fracture mechanics and its applications. In particular, the Swedish combined deterministic and probabilistic fracture mechanics procedure and associated computer code ProSACC can be named which has continuously been developed for safety assessment of components with cracks [39]. For example, probabilistic assessments using the ProSACC procedure has been applied for reactor pressure vessels in Sweden and for containers for final storage of spent nuclear fuel.

ProSACC has also been used in the international round robin project PROSIR (Probabilistic Structural Integrity of a PWR Reactor Pressure Vessel) aiming to develop recommendations on best practices for probabilistic analysis of RPV and to determine the key parameters influencing the RPV integrity [40].

Risk-informed approach for in-service inspection has been recognised by the industry for its potential to gain both safety and economy benefits. Since publication of the SSM regulation SKIFS 2000:2 it has been possible to use quantitative methods and risk-informed approach to ISI at nuclear power plants. For facilitating the use of RI-ISI in Sweden, a Structural Reliability Model (SRM) has been developed and implemented in the software package NURBIT (NUclear RBI Tool).

NURBIT is capable to quantify the risk levels for pipe rupture and leakage in piping having stress corrosion as the dominating damage mechanism [41]. NURBIT evaluates both leak- and rupture frequencies and combine them with the PSA system barriers to generate the risk of core damage (CCDF). The tool provides a risk ranking procedure to select an efficient inspection programme and inspection intervals. The deterministic models in NURBIT are advanced and take into account the whole sequence of crack initiation, subcritical growth until wall penetration and leakage and instability of the through-wall crack (pipe rupture). The model considers leak detection and recurrent inspections. However, the probabilistic evaluation in NURBIT is simplified and further development of more advanced probabilistic routines has been proposed.

In order to assure confidence in the results from probabilistic analyses, the underlying SRM models should be validated against available statistical data on pipe failure frequencies. This data is, however, very scarce for nuclear piping. Therefore, to evaluate the general behaviour and predicted trends for different SRM models they can be benchmarked and verified against each other.

Comprehensive studies for SRM benchmarking and verification were performed in the international project NURBIM [33]. As part of the project, the SRM model for SCC implemented in NURBIT code was evaluated along with other SRM models, e.g. WinPRAISE. The results from the NURBIM project demonstrated that NURBIT provides trends consistent with expectations, even though some differences existed between NURBIT and WinPRAISE. Differences are partly explained by the relatively simple probabilistic model in NURBIT, with limited possibilities of treating variables as random. However, NURBIT includes rather advanced deterministic models, e.g. transition of a surface crack to through-wall crack and evaluation of crack opening area for leak flow rate predictions.

Summing up, the probabilistic codes currently available and applied in Sweden are rather advanced. However, new technical challenges, new knowledge and changes in regulatory requirements may impose a need for further development and more comprehensive analyses, with the aim to improve understanding of different uncertainties and their effect on the predicted probabilities.

7.4 Potential for PRO-LOCA for independent assessment and verification

Probabilistic tools are valuable for Swedish nuclear industry and SSM in order to meet new challenges and support decision making. As a part of the development work to improve probabilistic tools in Sweden and provide quality assurance of probabilistic assessments, SSM has followed and participated in the development of the PFM code PRO-LOCA. This has been conducted through the projects MERIT [4] and PARTRIDGE.

The PRO-LOCA code is based on a SRM model where many parameters are defined probabilistically enabling a consistent treatment of uncertainties. The code is also capable of treating several degradation mechanisms such as low and high cycle fatigue, SCC and PWSCC. The rigorous probabilistic framework in PRO-LOCA also makes it a valuable analysis tool for establishing which parameters have the greatest impact on the overall results and which parameters make the largest contribution to the overall uncertainty.

These capabilities make PRO-LOCA very useful for *independent assessment* of results produced by other assessment codes and for *verification* of other Structural Reliability Models, since model verification is an important part of quality assurance.

Based on recommendations from the NURBIM project [33], SSM has formulated a set of requirements to a PFM code that have to be met in order to assure confidence in the results and allow its application in the nuclear facilities in Sweden [35]. These requirements for verification and validation are summarised below;

1. The technical basis of the PFM code should be published and independently reviewed.
2. A sensitivity study using the PFM model and the associated software should be presented where failure probabilities for events varying from small leaks to ruptures should be evaluated for variations of input parameters and shown to be consistent with expectations and the given PFM assumptions.
3. Sample calculations of the PFM code should be presented where the assigned input parameters should be described and sources of the data assignments should be given. The probability distributions and internally assigned parameters (if

any) in the PFM code should be documented and the reasons stated.

4. The PFM code should be benchmarked against at least one other publically available PFM code for the relevant damage mechanism under consideration. The report of this benchmark study should be published and independently reviewed.
5. The PFM code should be benchmarked against operating experience using actual plant failure and damage statistics. For damage mechanisms where no ruptures have occurred, leak frequencies may be used for the comparison.
6. The used software should be clearly identified. It is desired that new information or better modelling assumptions should be continuously incorporated into the PFM code so that the generated results may reflect the best current knowledge.

Similar requirements for assuring a reasonable level of confidence in the results and trends produced by a PFM code have been highlighted by NRC [42] and EPRI [37]. Considering a complexity of the PFM codes, it is essential to validate models, inputs and assumptions. In validation process it is important to perform it both at the model and at the integrated code level. If one output from the PFM code has been validated, it does not automatically assure validation for all outputs. Even small changes to inputs can have larger than expected or counterintuitive results due to complicated model interactions. Therefore, sensitivity studies are important for ensuring that results are being interpreted correctly.

The PRO-LOCA code fulfils the requirements above for verification, except for the requirement 4 regarding benchmarking against other publically available code. It would be interesting to benchmark it against NURBIT which has been benchmarked against other PFM codes in the NURBIM project [33]. NURBIT demonstrated adequate trends and behaviour, despite its simplicity in probabilistic modelling, probably supported by the very detailed and complete deterministic model taking into account the whole sequence of crack initiation, subcritical growth until wall penetration and leakage and instability. Implementation of improved probabilistic routines in NURBIT has been proposed.

PRO-LOCA can also be used for *independent assessment* of results produced by other assessment codes. PFM analyses using best estimate models and distributed inputs help gain insight into the driving uncertainties and evaluate significance of different uncertainties for a specific situation. However, independent sensitivity studies are valuable in order to confirm whether the applied model and data are sufficient or if more data is needed. Measures to demonstrate the values and uncertainty of driving parameters for the particular case may be recommended.

It can finally be noted that PRO-LOCA should be considered as a research code, as it is not fully quality assured and as it utilizes several separate underlying codes for different phenomena. To improve on this, NRC are developing the complete xLPR code in a strict quality assured manner. However, PRO-LOCA is still expected to provide very useful results when used with this remark in mind.

8 Discussion and conclusions

This report summarizes the activities of Inspecta Technology AB who followed development of the technical basis for the PFM code PRO-LOCA and evaluated the code under the PARTRIDGE project. This project has been conducted by the Battelle Memorial Institute (Columbus, Ohio, USA) aiming to take a further step in development of the probabilistic code PRO-LOCA.

The PRO-LOCA code is capable to predict the leak or rupture probabilities of nuclear piping systems taking into account the whole sequence of crack initiation, subcritical growth until wall penetration and leakage and instability of the through-wall crack (pipe rupture). The outcome of the PRO-LOCA code are a sequence of probabilities which represent the probability of a surface crack development, a through-wall crack development and six different sizes of crack opening areas corresponding to different leak flow rates or LOCA categories.

This report describes the current technical basis of the latest PRO-LOCA 4.0 code summarising the main improvements and changes introduced into PRO-LOCA as a result of the PARTRIDGE program. The report also gives a short introduction to practical aspects of using the PRO-LOCA code for probabilistic analyses.

Benchmark analyses and parametric sensitivity studies using PRO-LOCA are performed for two cases, a PWR pipe subject to PWSCC degradation, and a BWR pipe under fatigue cracking. As part of this study, the different aspects of PRO-LOCA capabilities and underlying models are assessed. The adequacy of the observed trends is discussed and compared with previous studies. Below are conclusions from the benchmark studies summarised, although it should be reminded that these conclusions are not general but based on a few cases.

The analyses of the PWR pipe case with active PWSCC degradation exhibit weak effect of crack geometry on predicted leak and rupture probabilities. Variation of fracture toughness demonstrate negligible influence on the calculated probabilities. These trends are in general agreement with results from other PFM codes in previous studies, e.g. NURBIM benchmark study for SCC [33]. Higher fracture toughness lead to larger critical crack size and consequently longer times to rupture, which should reduce the rupture probabilities. However, the results above show that in this case the influence of uncertainties in crack geometry and fracture toughness are very small.

The sensitivity analysis with respect to crack growth rate for PWSCC demonstrate very strong effect on predicted probabilities. This degradation mechanism is associated with high crack growth rates and uncertainties in these parameters are major drivers for leak and rupture probabilities. Weld residual stress distribution is another key parameter providing significant influence on rupture probability. The sensitivity analysis demonstrate that WRS mitigation significantly reduce SCC growth rates or may even provide a crack arrest situation.

The analyses of variation of inspection interval, leak detection capability and efficiency of NDT system (POD curve) demonstrate strong influences on the predicted probabilities for the PWR pipe case with PWSCC. Thus, when uncertainty related to PWSCC growth rate is large and difficult to quantify or control, the leak and rupture probability can be decreased by effective RI-ISI program and leak detection.

The analyses of the BWR pipe case with fatigue degradation exhibit a significant influence on probabilities from variation of the initial defect size. Similar trends were observed from other PFM codes in the fatigue benchmark study in NURBIM project [32]. However, the absolute values of calculated probabilities obtained by other PFM codes were lower than in this case.

Uncertainties in crack growth rate for fatigue has strong effect on the predicted probabilities. Variations of yield stress, ultimate tensile strength and fracture toughness demonstrate a weak effect on the calculated probabilities for leak and pipe rupture. Variation of inspection interval provide a strong influence on predicted probabilities also for the BWR pipe with fatigue degradation. However, the unexpected trend that the rupture probability increased with increasing ultimate tensile strength should be investigated further.

The resulting zero probabilities with PRO-LOCA for realistic leak detection limits (1-10 gpm) indicates that leak rate detection is a powerful way to detect leaks before a pipe break, i.e. the tendency for LBB is quite strong. If a reliable leak detection system is implemented in a pipe system, the only way a break can occur is when the stress state (i.e. system loads and weld residual stresses) are distributed in a way that an initiated circumferential crack will grow almost around the whole circumference before wall penetration. If then eventually a wall penetration occurs, the crack may be immediately unstable and a pipe rupture will occur.

Finally, the report presents discussion about relevance and importance of using PRO-LOCA and other PFM codes for the Swedish nuclear industry and regulatory body. The discussion considers existing regulatory requirements and application of probabilistic methods but also new requirements that may be introduced and new challenges that may arise under long term operation.

9 References

[1] NUREG-1829
"Estimating Loss-of-Coolant Accident (LOCA) Frequencies through the Elicitation Process. Main Report", U.S. NRC, Washington, DC, April 2008.

[2] Rudland, D., Xu, H., Wilkowski, G., Scott, P., Ghadiali, N. and Brust F.
"Development of a New Generation Computer Code (PRO-LOCA) for the Prediction of Break Probabilities for Commercial Nuclear Power Plants Loss-of-Coolant Accidents", PVP2006-ICPVT-11-93802, ASME 2006 Pressure Vessels and Piping/ICPVT-11 Conference, 2006.

[3] IAEA NP-T-3.13
"Stress Corrosion Cracking in Light Water Reactors: Good Practices and Lessons Learned", International Atomic Energy Agency, 2011.

[4] Scott, P., Kurth, R., Cox, A., Olson, R., and Rudland, D.
"Development of the PRO-LOCA Probabilistic Fracture Mechanics Code. MERIT Final Report", SSM report 2010:46, Swedish Radiation Safety Authority (SSM), 2010.

[5] Rudland, D., Scott, P., Kurth, R. and Cox, A.
"Continuing Development Of PRO-LOCA for the Prediction of Break Probabilities for Loss-of-Coolant Accidents", PVP2009-77053, ASME 2009 Pressure Vessels and Piping Conference PVP2009, 2009.

[6] ASME NQA-1.
Part I: Quality Assurance Requirements for Nuclear Facility Applications. 2008.

[7] Rudland, D., Harrington, C.
" Extremely Low Probability of Rupture (xLPR) Version 1.0 Code – Pilot Study Problem Results", PVP2011-57531, ASME 2011 Pressure Vessels and Piping Conference PVP2011, 2011.

[8] Kurth, R., Kurth, E., Young, B., Cox, A., Olson, R. and Scott, P.
"Benchmarking xLPR version 1.0 with the PRO-LOCA version 3.0 Code", PVP2012-78170, ASME 2012 Pressure Vessels and Piping Conference PVP2012, 2012.

[9] Kim, S.-H., Park, J.-S., Lee, J.-H., Yun, E.-S., Kang, S.-Y. and Shim, D.-J.
"Korean Consortium's preliminary research for enhancing a probabilistic fracture mechanics code PRO-LOCA", *International Journal of Pressure Vessels and Piping*, Vol. 131, pp. 75-84, 2015.

[10] Monthly Progress report No.7, PARTRIDGE program, January 2012.

[11] Kurth, R.
"Non-Standard Simulation Methods for Performing Extremely Low Probability Assessments", 13th International ASTM/ESIS Symposium on FFM (39th NFFM), Jacksonville, Florida, November 13-15, 2013. (https://www.researchgate.net/publication/281627523_Non-Standard_Simulation_Methods_for_Performing_Extremely_Low_Probability_Assessments).

[12] Kurth, R.
"PRO-LOCA 4.0 Updates Final", presentation at 2nd TAG Phone meeting, January 2014.

[13] User's Manual for PRO-LOCA Version 4.1.9 and PRO-LOCA GUI Version 4.0.4.8.
Draft 1. Battelle, February 2015.

[14] EPRI MRP-115 report.
"Materials Reliability Program: Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Alloy 82, 182, and 132 Welds", EPRI report 1006696, Palo Alto, CA, 2004.

[15] EPRI MRP-263 report.
"Materials Reliability Program: Technical Bases for the Chemical Mitigation of Primary Water Stress Corrosion Cracking in Pressurized Water Reactors (MRP-263 NP)", EPRI report 1025669, Palo Alto, CA, 2012.

[16] Bergman, M. and Brickstad, B.
"A Procedure for Analysis of Leak Before Break in Pipes Subjected to Fatigue or IGSCC Accounting for Complex Crack Shapes", *Fatigue & Fracture of Engineering Materials & Structures*, Vol. 18, No 10, pp. 1173-1188, 1995.

[17] Brickstad, B. and Sattari-Far, I.
"Crack Shape Developments for LBB-Applications", *Engineering Fracture Mechanics,* Vol. 67, pp. 625-646, 2000.

[18] Shim, D.-J., Rudland, D.
"Modelling of subcritical crack growth due to stress corrosion cracking transition from surface crack to through-wall crack", PVP2011-57267, ASME 2011 Pressure and Piping Conference PVP 2011, Baltimore, USA, 2011.

[19] Huh, N.S., Shim, D.-J.
"Stress intensity factors for slanted through-wall crack based on elastic finite element analyses", *Fatigue & Fracture of Engineering Materials & Structures*, Vol. 31, No. 2, pp. 197-209, 2008.

[20] Shim, D.-J., Kurth, R. and Rudland, D.
"Development of non-idealised surface to through-wall crack transition model", PVP2013-97092, ASME 2013 Pressure and Piping Conference PVP 2013, Paris, France, 2013.

[21] Shim, D.-J., Kurth, R. and Park, J.-S.
"Crack Transition Model for Circumferential Through-Wall Cracks", presentation at 2nd TAG Phone meeting, January 2014.

[22] Kurth, R. and Olson, R.
"Changes made to PRO-LOCA (V3.0Beta) since MERIT (V2.0)", presentation at 1st TAG meeting, Battelle, Columbus, June 2012.

[23] Rahman, S.
"Net-Section-Collapse Analysis of Circumferentially Cracked Cylinders - Part II: Idealized Cracks and Closed-Form Equations", *Engineering Fracture Mechanics,*
Vol. 61, pp. 213-230, 1998.

[24] Scott, P., Olson, R. and Wilkowski, G.
“Development of Technical basis for Leak-Before-Break Evaluation Procedures”; NUREG/CR-6765, May 2002.

[25] Young, B., Olson, R. and Kerr, M.
”Advances in COD equations: Circumferential through-wall cracks”, PVP2012-78181, ASME 2012 Pressure Vessels and Piping Conference PVP2012, 2012.

[26] Kurth, R. and Young, B.
“Future Improvement to PRO-LOCA”, presentation at 1st TAG meeting, Battelle, Columbus, June 2012.

[27] Scarth, D. and Xu, S.
“Universal Weight Function Consistent Method to Fit Polynomial Stress Distribution for Calculation of Stress Intensity Factor”, Journal of Pressure Vessel Technology, Vol. 134, 2012.

[28] Shim, D.-J., Kerr, M. and Xu, S,
“Effect of weld residual stress fitting on stress intensity factor for circumferential surface cracks in pipe”, PVP2012-78180, ASME 2012 Pressure and Piping Conference PVP 2012, Toronto, Canada, 2012.

[29] Shipsha, A., Sattari-Far, I. and von Feilitzen, C.
“Swedish experience with PRO-LOCA 3.0: Analysis results for Cases 11 to 19”,
presentation at 1st TAG meeting, Battelle, Columbus, June 2012.

[30] Rudland, D., Harrington, C. and Dingreville, R.
”Development of the Extremely Low Probability of Rupture (xLPR) Version 2.0 Code”, PVP2015-45134, ASME 2015 Pressure Vessels and Piping Conference PVP2015, 2015.

[31] Hiroto, I. et al.
“Benchmark analysis on PFM analysis codes for aged piping of nuclear power plants,” *Journal of Mechanical Science and Technology*, Vol. 26 (7), 2055~2058, 2012.

[32] Schimpfke, T.
"Review and benchmarking of SRMs and associated software. Appendix B - Fatigue benchmark study", NURBIM project, Fifth Framework of the European Atomic Energy Community (EURATOM), 2001.

[33] Brickstad, B.
"Review and benchmarking of SRMs and associated software. Appendix A1 - SCC benchmark study", NURBIM project, Fifth Framework of the European Atomic Energy Community (EURATOM), 2001.

[34] Knochenhauer, M.
"Challenges in nuclear power – regulator's perspective", Department of Nuclear Power Plant Safety, SSM, presentation at Nuclear Technology 2015 conference, Stockholm, 2015.

[35] Brickstad, B.
"On the Use of Probabilistic Methods and PFM for Regulatory Applications in Sweden", Department of Nuclear Power Plant Safety, SSM, presentation at U.S. Nuclear Regulatory Commission's (NRC's) Regulatory Information Conference (RIC) 2016, Rockville, 2016.

[36] Brickstad, B.
"Guidelines for analysis of pipe break protection in Nuclear Facilities" (in Swedish), SSM 2008/200, SSM Report, January 2010.

[37] Palm, N.A.
"EPRI Perspectives on the Use of Probabilistic Fracture Mechanics",
EPRI, presentation at U.S. Nuclear Regulatory Commission's (NRC's) Regulatory Information Conference (RIC) 2016, Rockville, 2016.

[38] Nilsson, F., Brickstad, B. and Skånberg, L.
"Pipe break probabilities due to IGSCC", *Int. J. Pres. Vessels and Piping*, Vol. 43,
205-217, 1990.

[39] Dillström, P., Bergman, M., Brickstad, B., Zang, W., Sattari-Far, I., Andersson, P., Sund, G., Dahlberg, L. and Nilsson, F. "A combined deterministic and probabilistic procedure for safety assessment of components with cracks – Handbook", SSM report 2008:01, 2008.

[40] Dillström, P. "PROSIR - Probabilistic Structural Integrity of a PWR Reactor Pressure Vessel", SSM report 2015:09, 2015.

[41] Brickstad, B. and Zang, W. "NURBIT, NUclear RBI analysis Tool, A Software for Risk Management of Nuclear Components", DNV Technical Report 10334900-1, 2001.

[42] Rudland, D. "Thoughts on Increasing Confidence in Probabilistic Fracture Mechanics Analyses", U.S. NRC, presentation at U.S. Nuclear Regulatory Commission's (NRC's) Regulatory Information Conference (RIC) 2016, Rockville, 2016.

2016:37

The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 300 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

Strålsäkerhetsmyndigheten
Swedish Radiation Safety Authority

SE-171 16 Stockholm
Solna strandväg 96

Tel: +46 8 799 40 00
Fax: +46 8 799 40 10

E-mail: registrator@ssm.se
Web: stralsakerhetsmyndigheten.se