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Regulatory Perspective on PFM and Risk-Informed Methodologies in Sweden

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Outline

- Situations when probabilistic methods and PFM are used to support regulatory decisions in Sweden.
  - LBB applications
  - RI-ISI
  - Analyzing service-induced damages for continued operation of mechanical components
  - Periodic Safety Reviews
- How to gain confidence in PFM results.

The new Regulatory Code SSMFS 20XX:YY for Analysis of Radiation Safety of Nuclear Power Plants (ongoing development)

About pipe ruptures

The most challenging pipe ruptures shall be postulated as design basis accidents regarding core cooling and reactor isolation.

However, if the occurrence frequency with high confidence can be shown to be lower than 1E-6 per year, then such pipe ruptures can be postulated as design extension conditions (DEC). An example of such situation is when LBB can be demonstrated.

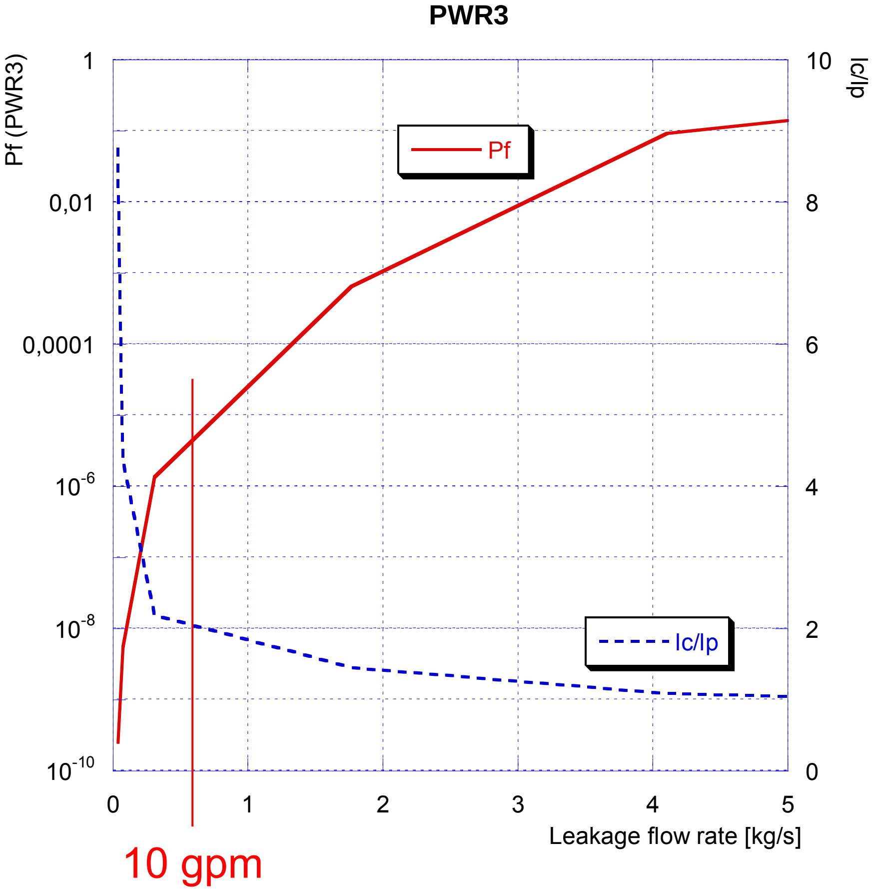
Probabilistic insights for LBB

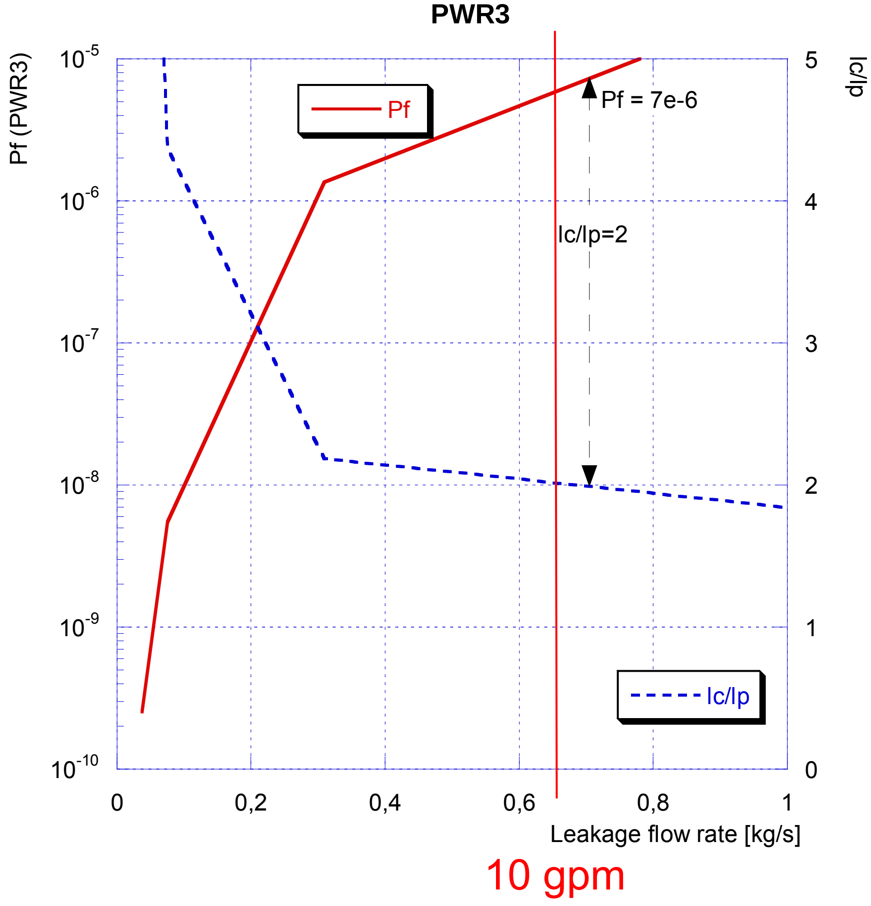
- Probabilistic analyses may strengthen the assessment that there is a sufficiently low probability for a pipe rupture and that there is a sufficient margin between initial detectable leak and break.
- A probabilistic analysis should be able to demonstrate that the frequency of a pipe break is so low that it can be considered as a residual risk.

- SSM has financed a project in Sweden called ProLBB. In this project the deterministic criteria used in the LBB guidelines (NUREG/CR-6765) are compared with a probabilistic analysis.
- The resulting Research Report 2007:43 can be downloaded from our website.

ProLBB-results, thick-walled PWR pipe

The figure shows the conditional rupture probability (using normal operating loads) for a PWR pipe (D = 872 mm, t = 65 mm). The deterministic values of l_c/l_p are also shown.

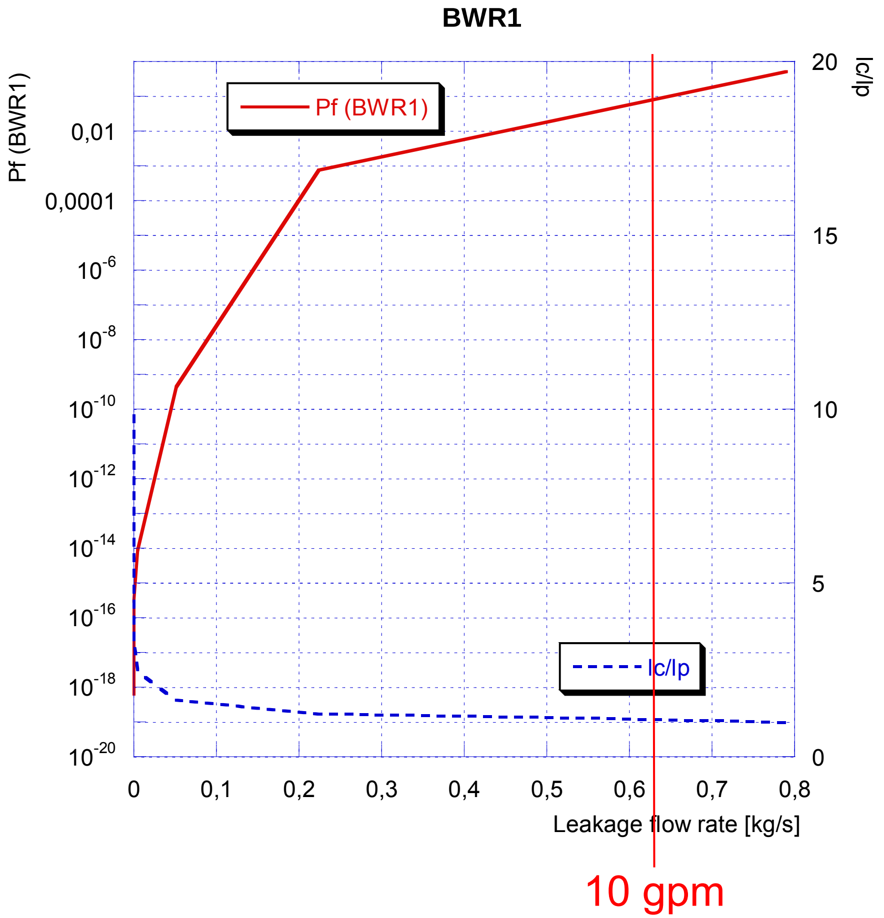


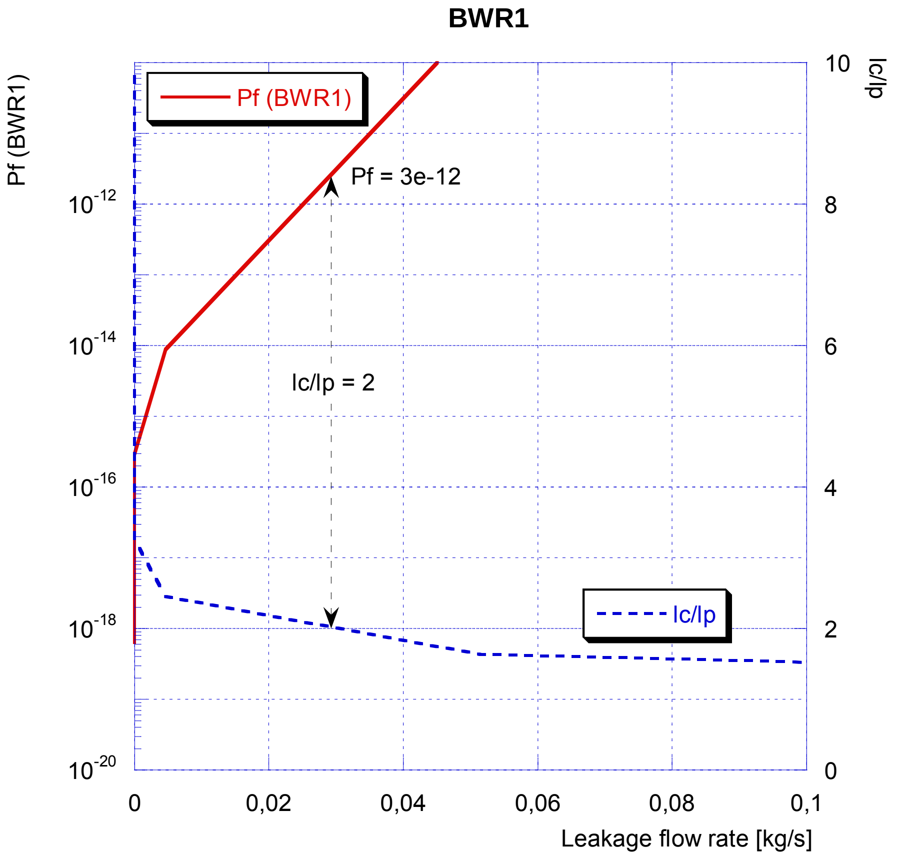


$l_c/l_p = 2 \;\rightarrow\; p_f \approx 7e\text{-}6$ (leakage ≈ 0.7 kg/s, 11 gpm)
This leak rate is easy to detect.

ProLBB-results, thin-walled BWR pipe

The figure shows the <u>conditional</u> rupture probability (using normal operating loads) for a BWR pipe (D = 114 mm, t = 8 mm). The deterministic values of I_c/I_p are also shown.



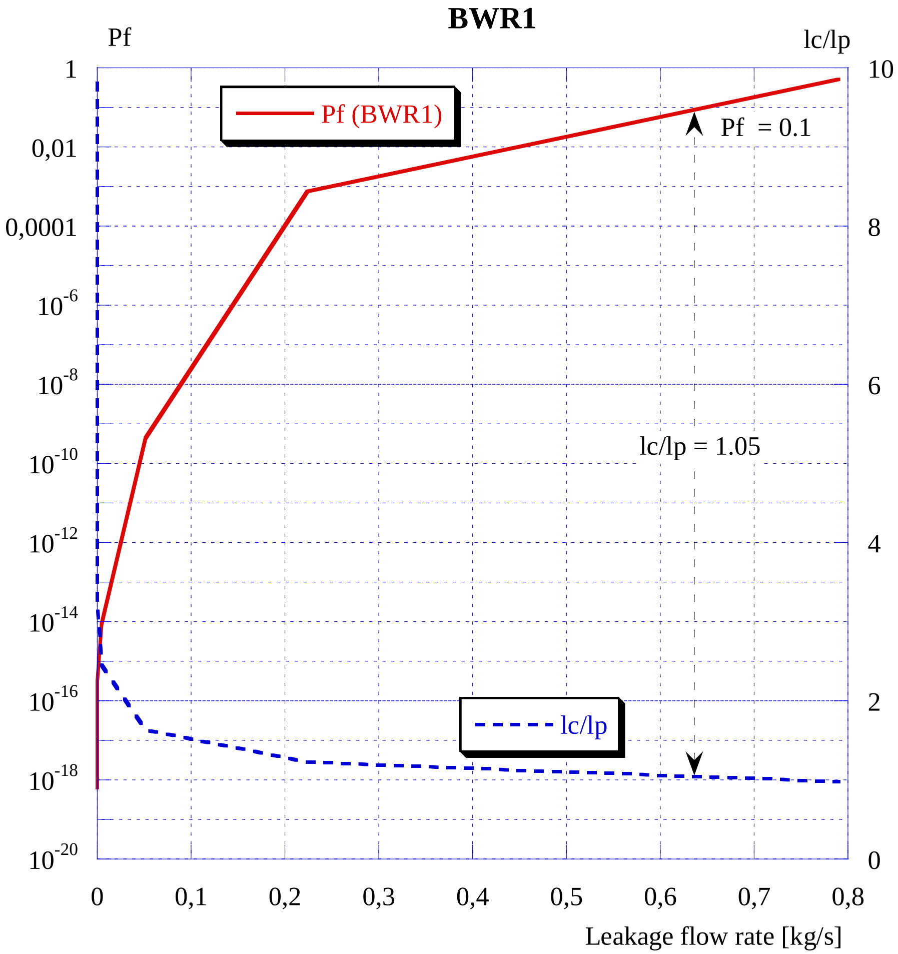


$I_c/I_p = 2 \rightarrow p_f \approx 3e\text{-}12$ (leakage ≈ 0.03 kg/s, 0.5 gpm)

This leak rate is more difficult to detect if a margin on 10 on leak rate is desired.

ProLBB-results, thin-walled BWR pipe

This figure below shows the same results as for the previous figure but extended to higher leak rates



For a leak rate of 0.63 kg/s (10 gpm) the margin l_c/l_p is only 1.05.
This explains why it is more difficult to fulfil the deterministic LBB-margins for a small diameter pipe compared to a large diameter pipe.

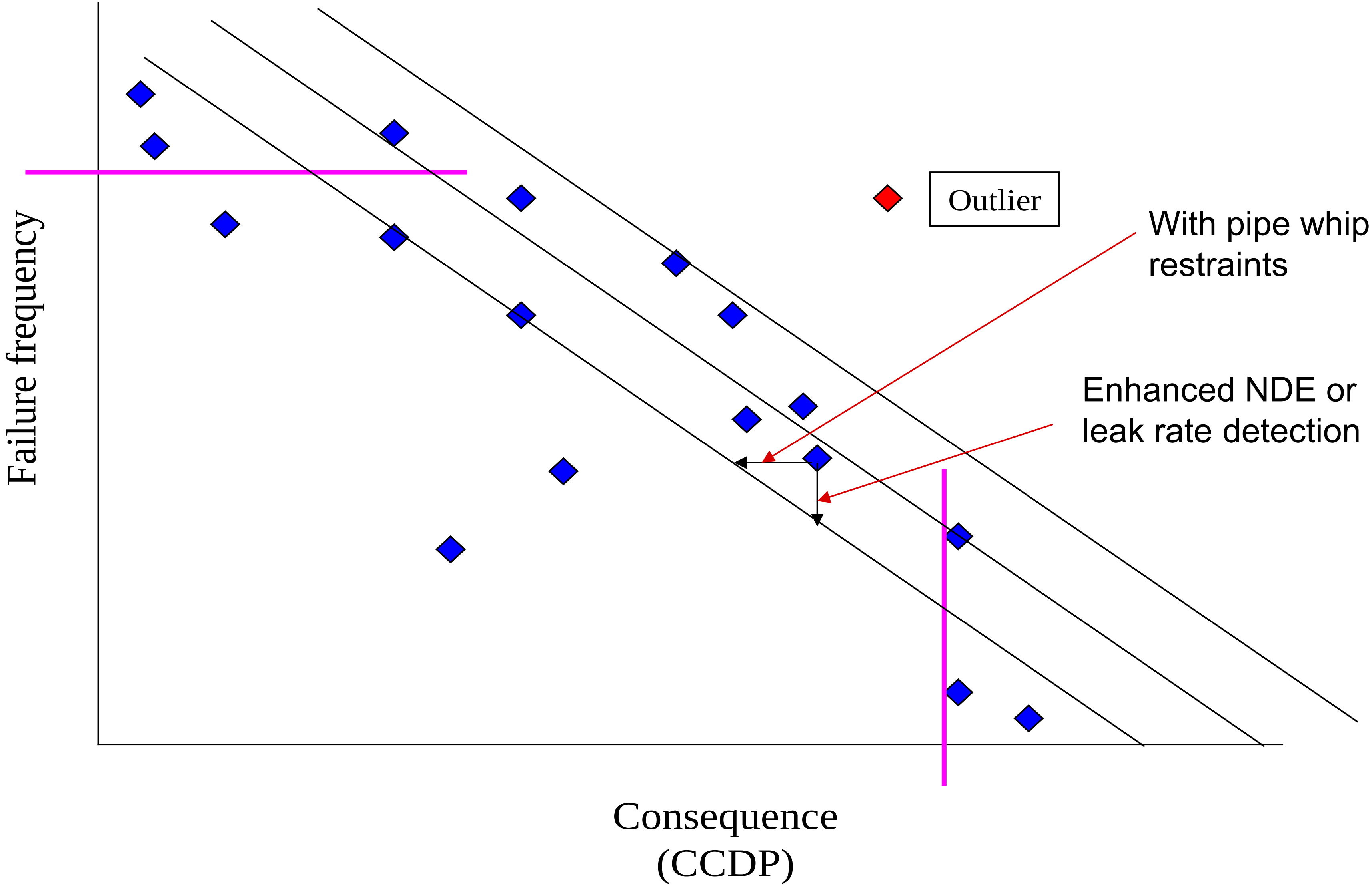
Further studies on LBB

- Investigate the possibility to develop a risk-informed LBB-concept. The consequences of a pipe break with and without pipe whip restraints can be estimated with PRA and changes in failure frequencies can be estimated from enhanced NDE and/or enhanced leak rate detection. Possibly, these measures can be shown to be equivalent.

- Investigate the possibility to develop a probabilistic LBB-concept based on acceptance criteria for a low p_{break} and for a sufficiently low p_{break}/p_{leak}. Such a concept may perhaps also be applied for piping with degradation mechanisms together with mitigating actions.

- Investigate more realistic crack shapes for pipes when active damage mechanisms are present.

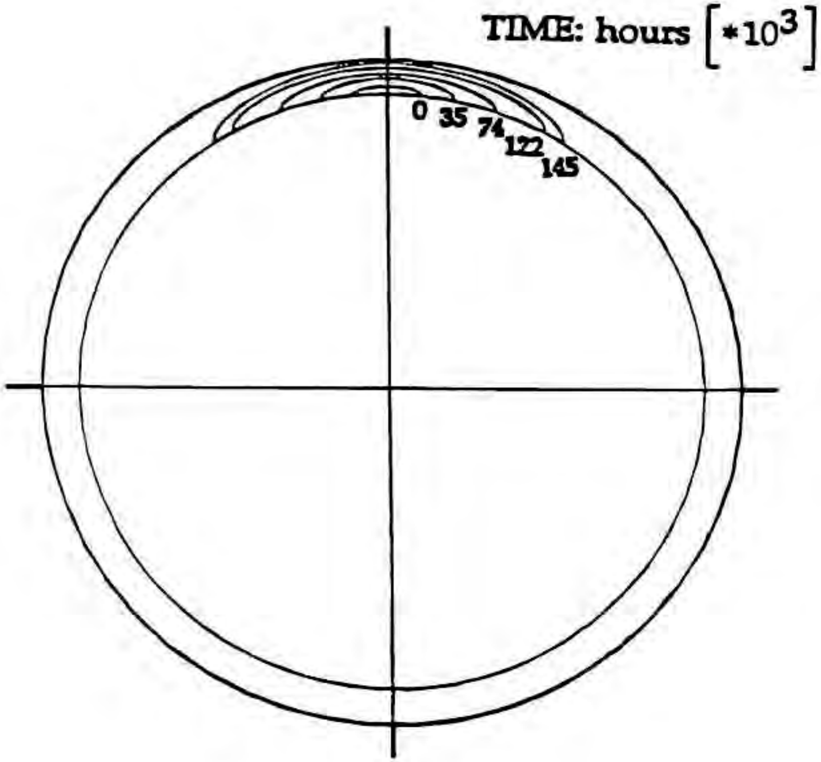
Risk-informed LBB-concept (for future studies)

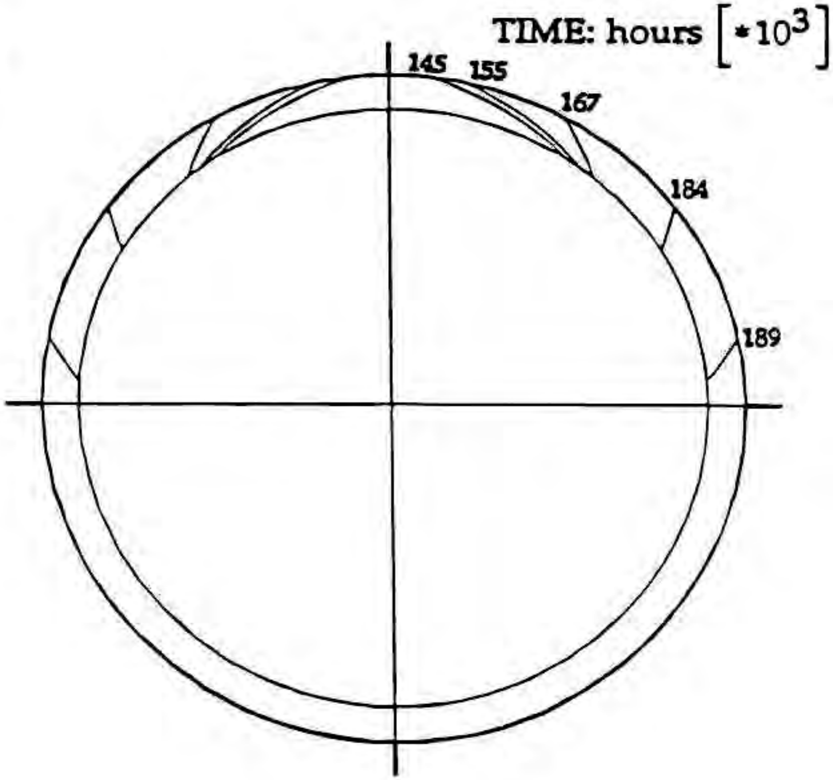


- Is it possible to predict the crack growth and to estimate the leak- and rupture probability for pipes containing more realistic crack shapes when SCC is an active damage mechanism?

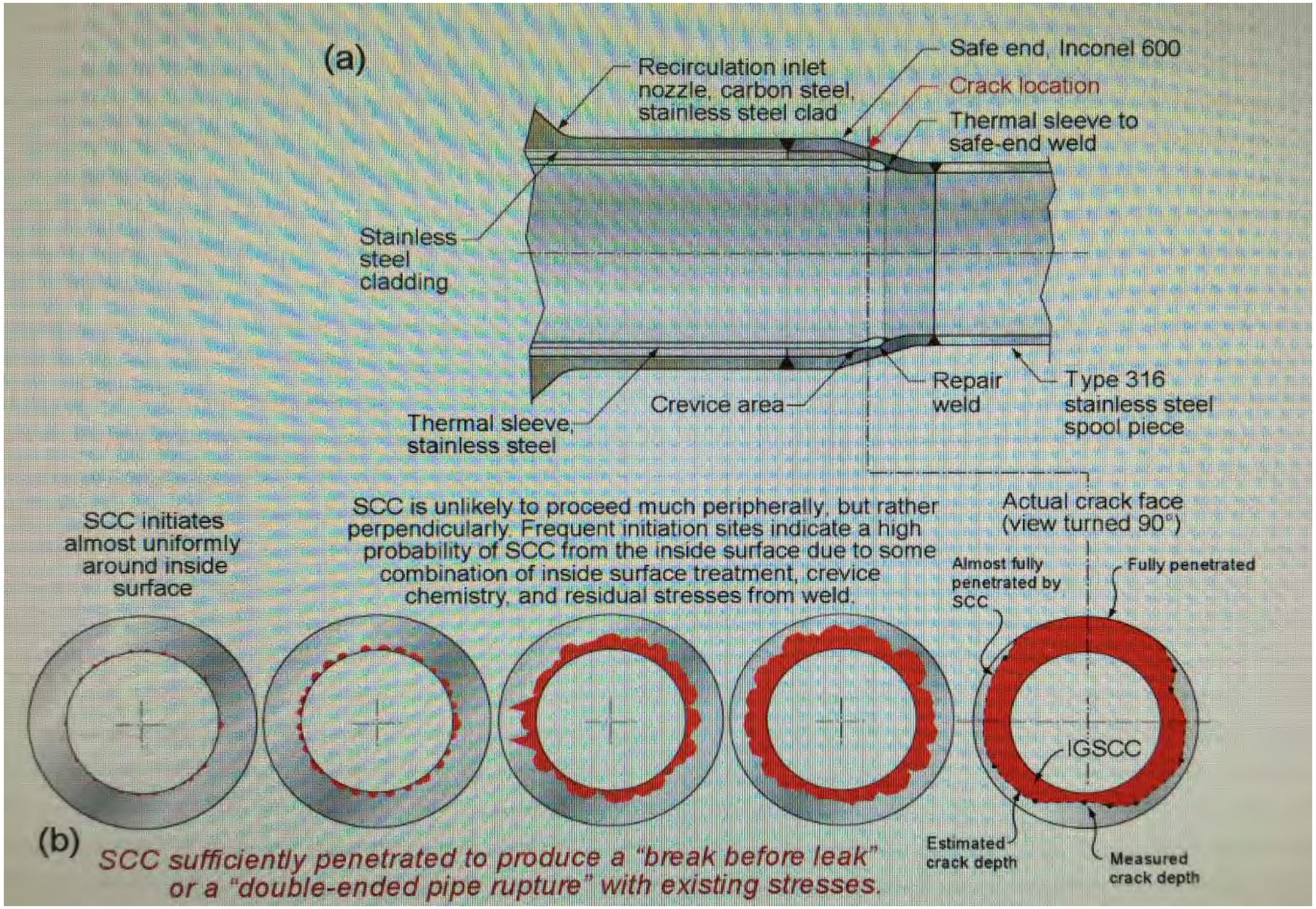
- Deterministic and probabilistic insights

These figures are examples of how a stress corrosion crack is predicted to propagate in the vicinity of a girth weld in a 26 inch stainless steel pipe. The local weld residual stress (tension compression-tension) will create a larger crack growth at the inside of the pipe. In some situations the WRS and the system stresses may create a full circumferential surface crack before leak is predicted. This means that there is a smaller tendency for LBB!





At least one example of a full circumferential surface crack from SCC has occurred. It is Duane Arnold NPP in 1978, where a 360 degrees circumferential IGSCC was found at the feedwater nozzle safe end and finally leaking at a 80 degrees sector of the circumference



SCC initiates almost uniformly around inside surface

SCC is unlikely to proceed much peripherally, but rather perpendicularly. Frequent initiation sites indicate a high probability of SCC from the inside surface due to some combination of inside surface treatment, crevice chemistry, and residual stresses from weld.

SCC sufficiently penetrated to produce a "break before leak" or a "double-ended pipe rupture" with existing stresses.

About service-induced damages in Swedish NPPs, Swedish Regulations SSMFS 2008:13, Chapter 2, § 6

A device where damages have been detected, may be kept for continued operation, without repair or replacement, when it has been demonstrated that sufficient safety margins exist against failure and such leakages and other deficiencies which can influence the safety during the operation period in question.

- Deterministic analyses shall be performed to demonstrate sufficient safety margins. The analysis methods shall be validated and based on well established techniques and using qualified material data and growth rates. In these analyses, the R6 Failure Assessment Diagram are recommended with safety margins comparable to ASME XI.

- New Regulatory Code: In cases where deterministic analyses have shown that there is not enough safety margins or if other uncertainties exist, SSM recommends to perform probabilistic analyses. Such analyses can be a valuable complement to deterministic evaluations in order to make a better decision regarding the safety of a damaged reactor component.

Regulatory aspects on Periodic Safety Reviews (PSR)

- A PSR shall be done by the licensees every 10 years in Sweden.
- The PSR shall demonstrate that the NPP can still be safely operated during the next 10 years. Account shall be taken to the development within science and technology.
- For demonstration of sufficient structural integrity of the RPV with respect to neutron embrittlement, SSM has recommended that NPPs shall perform both a deterministic and a probabilistic analysis.
- The probabilistic analysis based on PFM should confirm that the failure frequency is small enough not to contribute significantly to the total CDF of the plant. This represents an acceptance criteria!

- One example of a PSR which involved PFM is Ringhals-2, which is a Westinghouse PWR.
- This reactor has a lot of under-clad cracks (UCC).
- The licensee performed both a deterministic and a probabilistic analysis to verify the integrity.
- The PFM analysis verified that the leak- and rupture probabability from the UCC was very small.
- In addition, the licensee performed an eddy-current testing of the cladding in the core region to verify that there were no surface breaking cracks.

How do you gain confidence in PFM results?

- SSM requires that models and computer codes used for PFM shall be sufficiently verified and validated.
- SSM recommends to use the results from NURBIM.

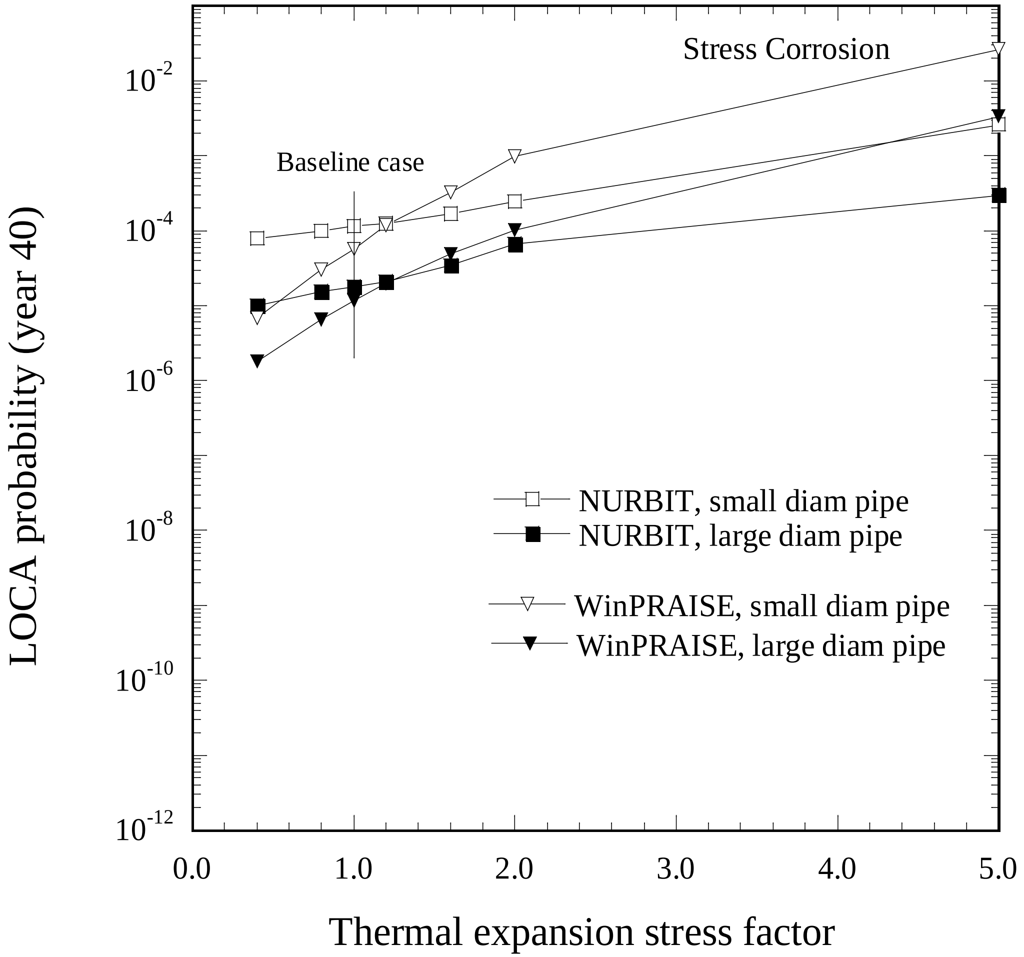
NURBIM = NUclear Risk Based Inspection Methodology for passive components

- EU-funded project, budget 1.2 million Euro
- Duration: November 2001 to July 2004
- 12 participating organisations from 8 European countries: Sweden, Germany, France, UK, Netherlands, Spain, Czech Republic and Finland
- Presented at the ASME PVP in San Diego, 2004 by Brickstad et al.

Objectives of NURBIM

- Review PFM models and associated software in terms of main features, capabilities and limitations.
- Benchmark PFM models and associated software for SCC and fatigue by performing a comprehensive sensitivity study and compare results.
- Investigate the reasons for differences in results from the benchmark studies and identify strengths and weaknesses of the PFM codes.
- Issue recommendations for how to verify and validate PFM models and associated software.

Example of NURBIM results



- Are the PFM codes generating a wide range of failure probabilities (1E-10 to 1)?
- Is the result consistent with expectations?
- Expected risk ranking between different pipe sizes and using different PFM codes?
- For differences in behaviour, there should exist a justified PFM theory explanation.

Recommendations from the NURBIM project

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

2. A sensitivity study using the PFM and the associated software should be presented where failure probabilities for events varying from small leaks to ruptures, should be evaluated for systematic variations of input parameters. The sensitivity study shall be consistent with expectations and with the given PFM theory 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 (hardwired) parameters (if any) in the PFM code should be documented and the reasons stated.
4. When rupture probabilities in pipes are evaluated, it is important to be able to model LBB events. This requires an adequate model of crack opening areas, leak flow rates and leak flow rate detection.

5. 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.

6. The PFM code should be benchmarked against operating experience using actual plant failure frequencies. For damage mechanisms where no ruptures have occurred, leak frequencies may be used for the comparison.

7. The applied 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.

Final notes

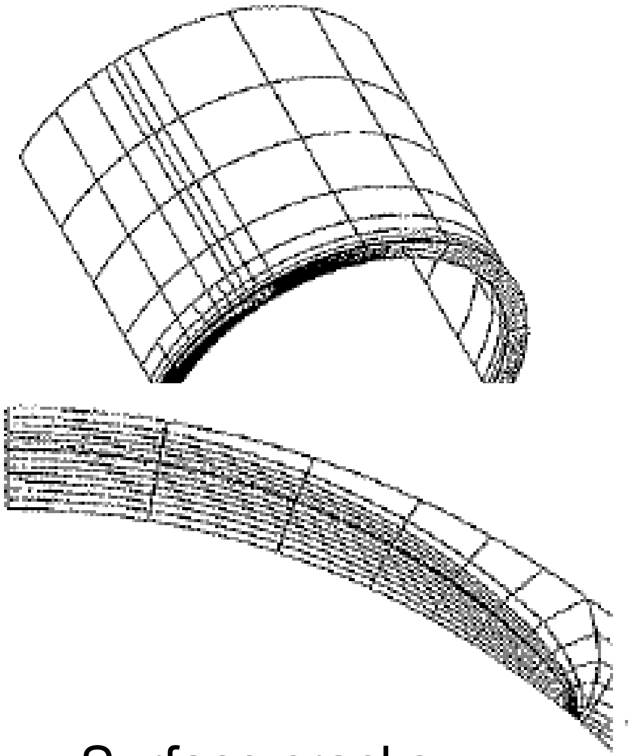
A PFM code can only give information of the integrated models which are included in the code. The PFM code can be said to be a measure of our current knowledge!
However, it cannot tell you anything about the unexpected (e.g. human mistakes or known degradation mechanisms occurring at unexpected locations.)

It is difficult to validate small values of the failure probability which is expected for slow-growing cracks. For these reasons it can be difficult and perhaps not even advisable to state what is an acceptable failure probability. On the other hand, a probabilistic analysis represents a systematic way of treating uncertainties and can give useful information of which uncertainty that is influencing the failure probability most.

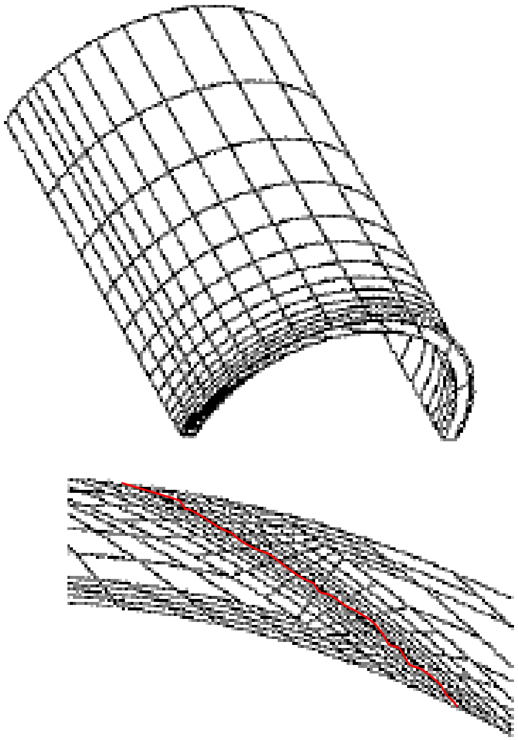
Backup slides

About complex crack shapes

Using 3D-FEM a database has been created generating influence functions for the local K along the crack front for complex crack shapes for stresses up to 3rd degree polynomial plus global ben ding. The local K-values along the crack front are used and then a least square method is used to map the shape onto a set of “allowed” crack shapes.



Surface cracks



Through-wall cracks

References

Bergman M. & Brickstad B., A Procedure for Analysis of LBB in Pipes subjected to Fatigue or IGSCC Accounting for Complex Crack Shapes, *Fatigue Fract. Engng. Mater. Struct.* Vol. 18, No. 10, pp. 1173-1188, 1995.

Brickstad, B. & Sattari-Far, I., Crack Shape Developments for LBB Applications, *Eng. Fract. Mech.* Vol. 67, pp. 625-646, 2000.