Regulatory Aspects on the Application of the LBB Concept for Swedish Nuclear Power Plants

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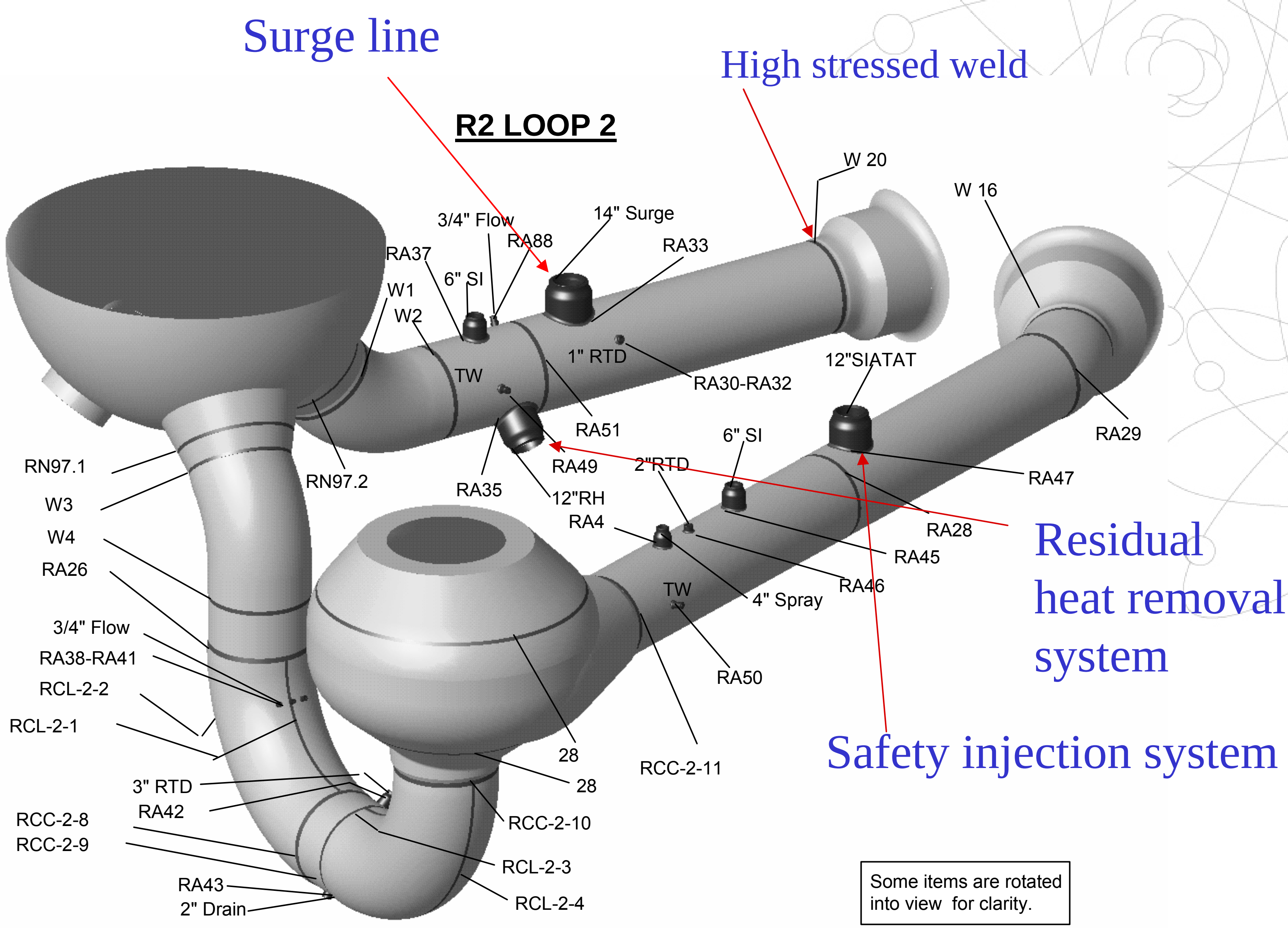
Ongoing review of LBB-applications to SKI

Ringhals unit 2 has applied to SKI for using LBB for the following pipe segments:

- Reactor coolant loops (cold leg, hot leg, cross over leg).
- Surge line (from hot leg to pressurizer).
- Residual heat removal system (high pressure part).
- Safety injection system.

Ringhals unit 2 was built in the early seventies during which not many pipe whip restraints were installed in the primary system.


Surge line
High stressed weld
R2 LOOP 2
W 20
W 16
3/4" Flow
14" Surge
RA88
RA33
RA37
6" SI
W1
W2
1" RTD
TW
RA30-RA32
12"SIATAT
RA51
6" SI
RA29
RN97.1
RA49
2"RTD
RA47
RN97.2
RA35
W3
12"RH
RA4
RA28
W4
RA45
Residual
heat removal
system
RA26
TW
RA46
4" Spray
3/4" Flow
RA38-RA41
RA50
RCL-2-2
RCL-2-1
Safety injection system
28
RCC-2-11
3" RTD
28
RA42
RCC-2-8
RCC-2-10
RCC-2-9
RCL-2-3
RA43
2" Drain
RCL-2-4
Some items are rotated into view for clarity.

Problem areas

1. The applicant has used an in-house code for leak rate evaluations together with unrealistic crack morphology parameters which tend to overestimate the deterministic LBB-margins.
2. SKI does not in general allow the use of LBB for not having to consider effects from the asymmetric blowdown loads if rupture occurs on the RCL. This is because an entire safety function may be jeopardized.
3. The weld connecting the safe-end to the surge line nozzle is made of Alloy 182, known to be susceptible to PWSCC.

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Deterministic LBB-margins

- SKI has funded work to recalculate the applicant's LBB-margins using SQUIRT and more realistic crack morphology parameters. Also, the critical crack size is determined using the R6-method. The resulting SKI Report 2007:39 can be downloaded or ordered from our website www.ski.se.

Case	Crack morphology	Leakage crack size
1	Applicant[1]	Leakage is 10 gpm
2	Fatigue[2]	Leakage is 10 gpm
3	Fatigue[2]	Calculate the leakage rate when the leakage crack size is one half of the critical crack size

1) $\mu = 300$ μinch, $\eta = 0$.
2) $\mu_G = 1594$ μinch, $\eta_G = 0.673$ velocity heads per mm.

Margins for crack length (Case 1 and 2) and margins for leakage rate (Case 3) for five welds in the Residual heat removal system (using the code ProSACC to determine the critical crack size, using the code NURBIT to evaluate COA and using SQUIRT to evaluate leak flow rates.)

Location	Applicant critical crack size (mm)	Average critical crack size by ProSACC (mm)	Margin for Case 1 *lc/lp*	Margin for Case 2 *lc/lp*	Leakage rate for Case 3 (gpm)
L1W1	405	318	1.80	1.49	2.19
L1W2	427	336	1.84	1.51	2.30
L2W1	279	222	1.82	1.43	2.75
L2W2	310	247	1.88	1.50	3.09
L2W3	320	254	1.94	1.53	3.43

Observations

- Crack morphology parameters have a strong influence on the leak rate evaluations. Using the SQUIRT code and more recent recommendations for crack morphology parameters, it is shown that in many cases the evaluated margins are below the safety factor of 2 on crack size and 10 on leak rate, which is generally required for LBB approval.
- This will have an impact on the SKI staff review on the capability of the leak rate detection systems.

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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.
- SKI has funded a project in Sweden called ProLBB. In this project the deterministic criteria used in the current LBB guidelines are compared with a probabilistic analysis.
- In these evaluations, no active degradation mechanisms are assumed, only a flaw distribution from welding defects.
- 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.
- The resulting SKI Report 2007:43 can be downloaded or ordered soon from our website www.ski.se.

Probabilistic LBB approach – ProLBB code

- What is calculated using ProLBB?
  - Probability of leakage (given the existence of a small surface crack).
  - Probability of rupture (given the existence of a leaking through-thickness crack).

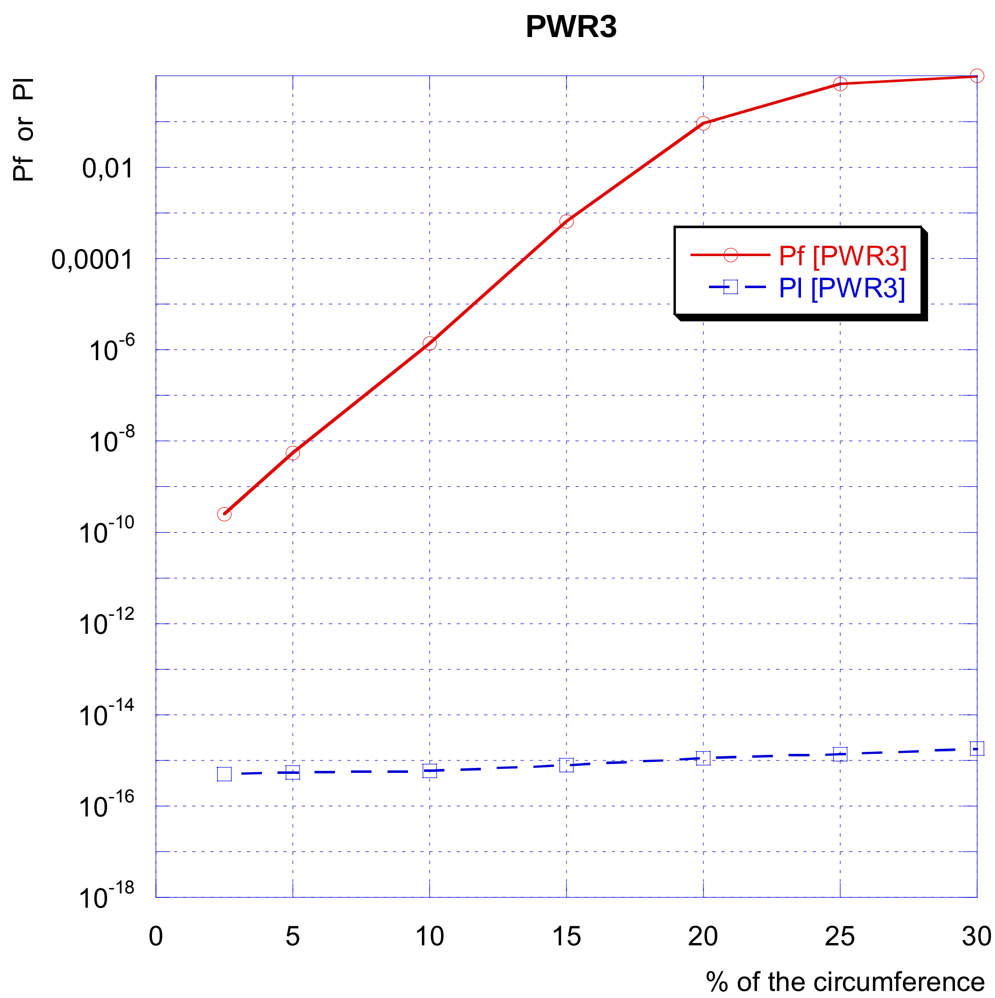
- Methods used to calculate the different probabilities:
  - Monte Carlo Simulation (MCS), only used to check the results using the other methods.
  - First Order Reliability Method (FORM).
  - Monte Carlo Simulation with Importance Sampling (MCS-IS).

ProLBB code

- Deterministic parameters
  - Pipe diameter (D_y)
  - Pipe wall thickness (t)
  - Internal pressure (p)
  - Temperature (T)
  - Leakage flow rate
  - Crack morphology variables

- Probabilistic parameters
  - Crack size, surface crack (a, l)
  - Crack size, through-thickness crack (l)
  - Off-centred position of crack (ψ)
  - Fracture toughness (K_{Ic}, J_{Ic})
  - Yield strength (σ_y)
  - Ultimate strength (σ_y)
  - Primary stresses (P_m, P_b)
  - Secondary stresses (P_e, σ_{weld})

The figure shows the leak probability and the conditional rupture probability for a specific weld (PWR3) in the hot leg of the PWR plant.



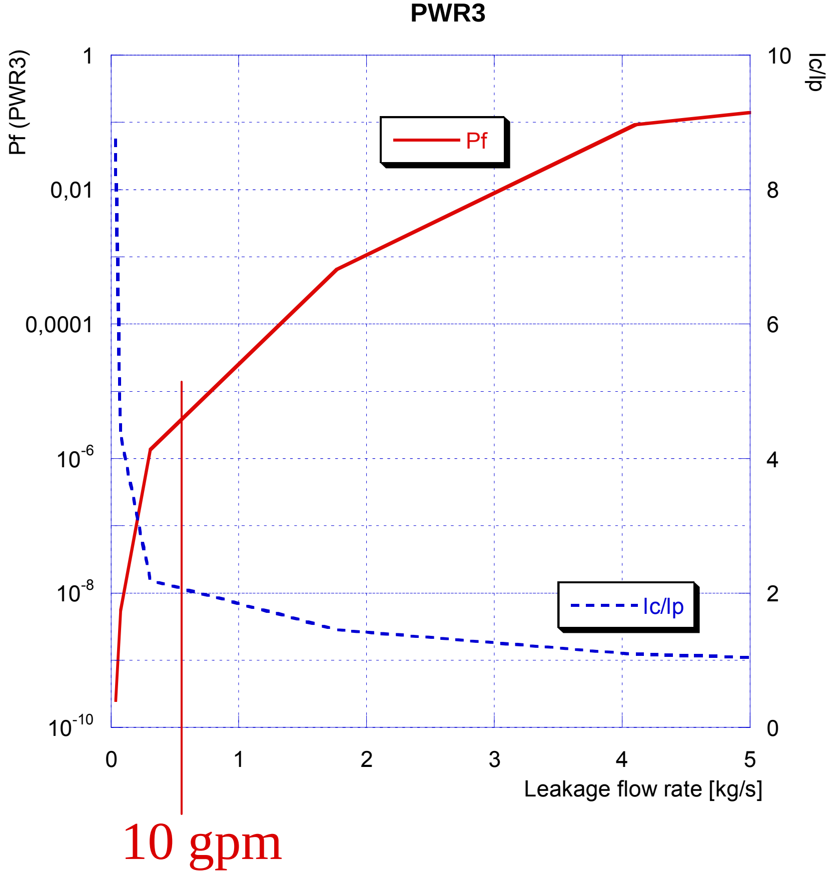
PWR3

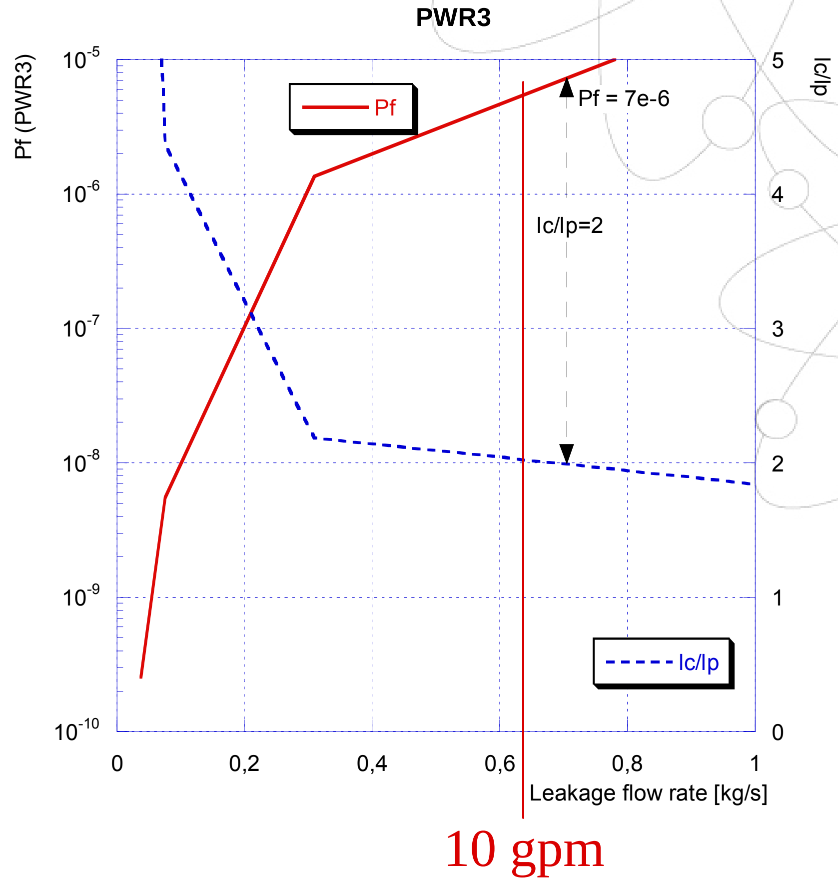
D = 871.5 mm (34.3 in)

T = 64.9 mm (2.55 in)

How does the deterministic LBB margins relate to the conditional rupture probability?

PWR3

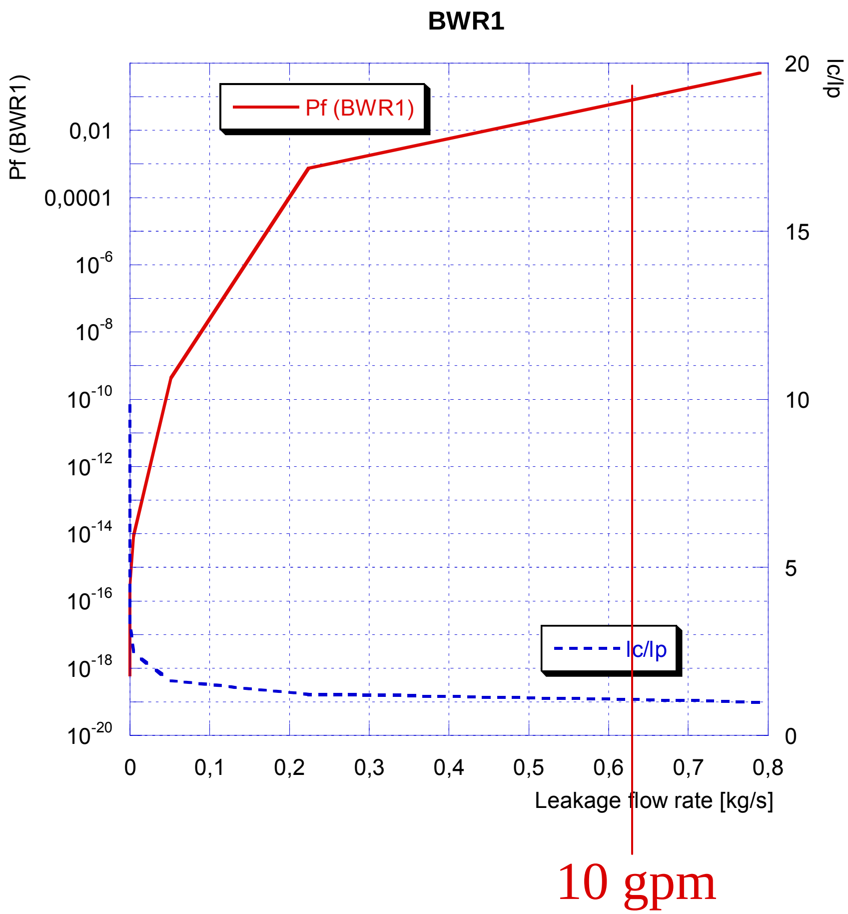


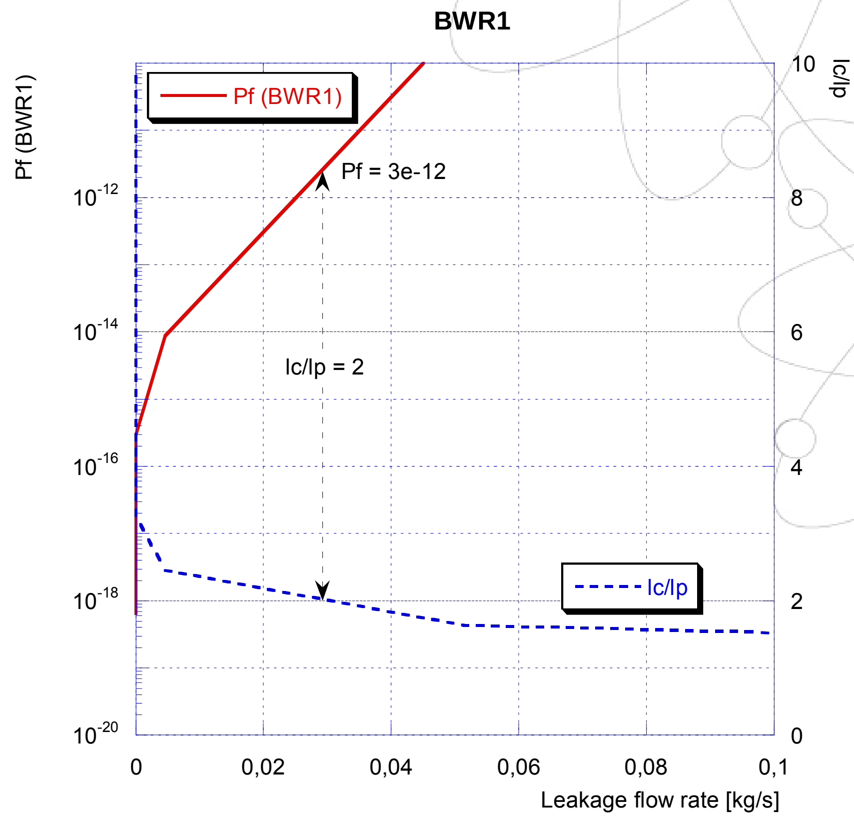


$l_c/l_p = 2 \rightarrow P_f \approx 6.5E\text{-}6$ (leakage ≈ 0.68 kg/s or 10.8 gpm)

The figures show the corresponding results for a small diameter pipe in a BWR plant.

BWR1
D = 114 mm (4.5 in)
T = 8 mm (0.31 in)





$l_c/l_p = 2 \rightarrow P_f \approx 3.4E\text{-}12$ (leakage ≈ 0.03 kg/s or 0.48 gpm)

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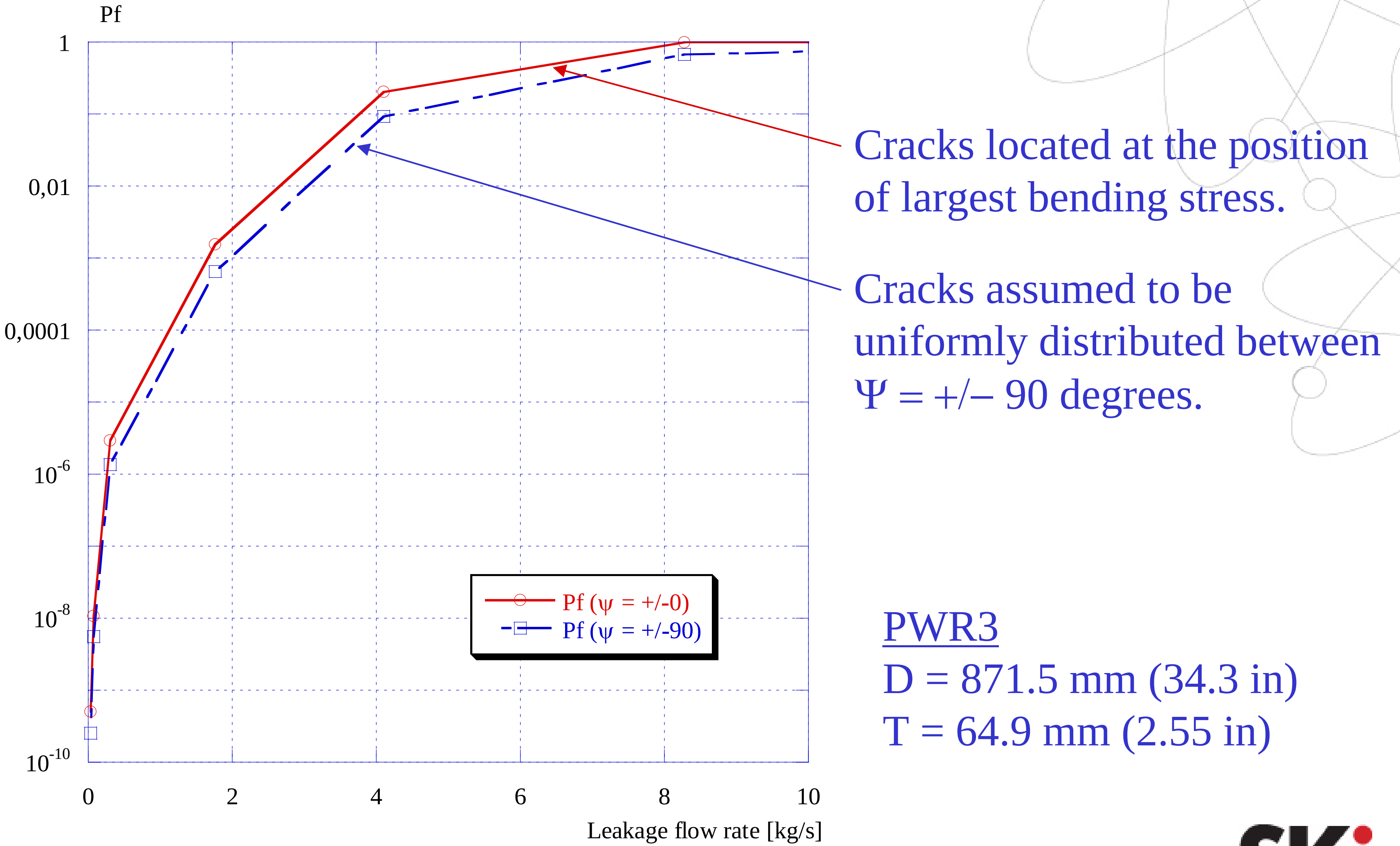
The figure shows the effect of off-centered cracks in terms of the conditional rupture probability versus leak flow rate.



PWR3
D = 871.5 mm (34.3 in)
T = 64.9 mm (2.55 in)

Observations

- If no active degradation mechanisms exist, the resulting leak- and rupture probabilities will be extremely small.
- This supports the belief that LBB prevails for the RCL.
- The probabilistic results give some explanations why it is more difficult to fulfill the deterministic LBB criteria for a small diameter pipe compared to a large diameter pipe.
- It is very conservative to assume the existence of a leaking crack in a pipe when there is no potential for any active degradation mechanism.
- The influence of off-centered cracks seem to be small when no active degradation mechanism is assumed.
- These results will have an impact on the SKI staff review on the LBB application for the RCL.

Problem areas

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2. SKI does not in general allow the use of LBB for not having to consider effects from the asymmetric blowdown loads if rupture occurs on the RCL. This is because an entire safety function may be jeopardized.
3. The weld connecting the safe-end to the surge line nozzle is made of Alloy 182, known to be susceptible to PWSCC.

Surge line, connection to pressurizer

Alloy 182
weld

Inspection results 2000, Ringhals unit 4 (in operation since 1983)

Several indications recorded in one safe end in the RCL outlet nozzle to safe end, evaluated as

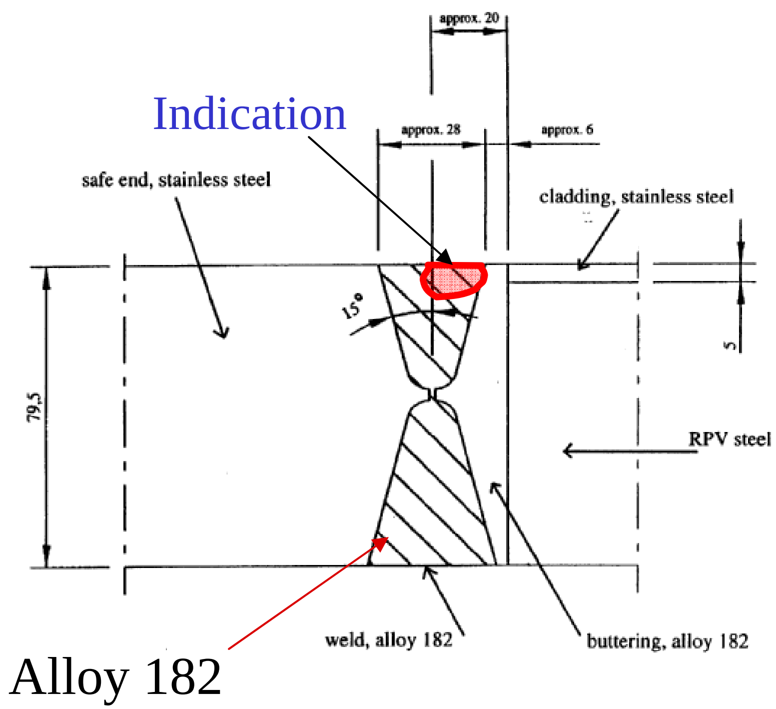
- volumetric defects
- 3 sub surface planar flaws and 1 surface planar flaw > qualification targets

Planar flaws removed by boat samples to

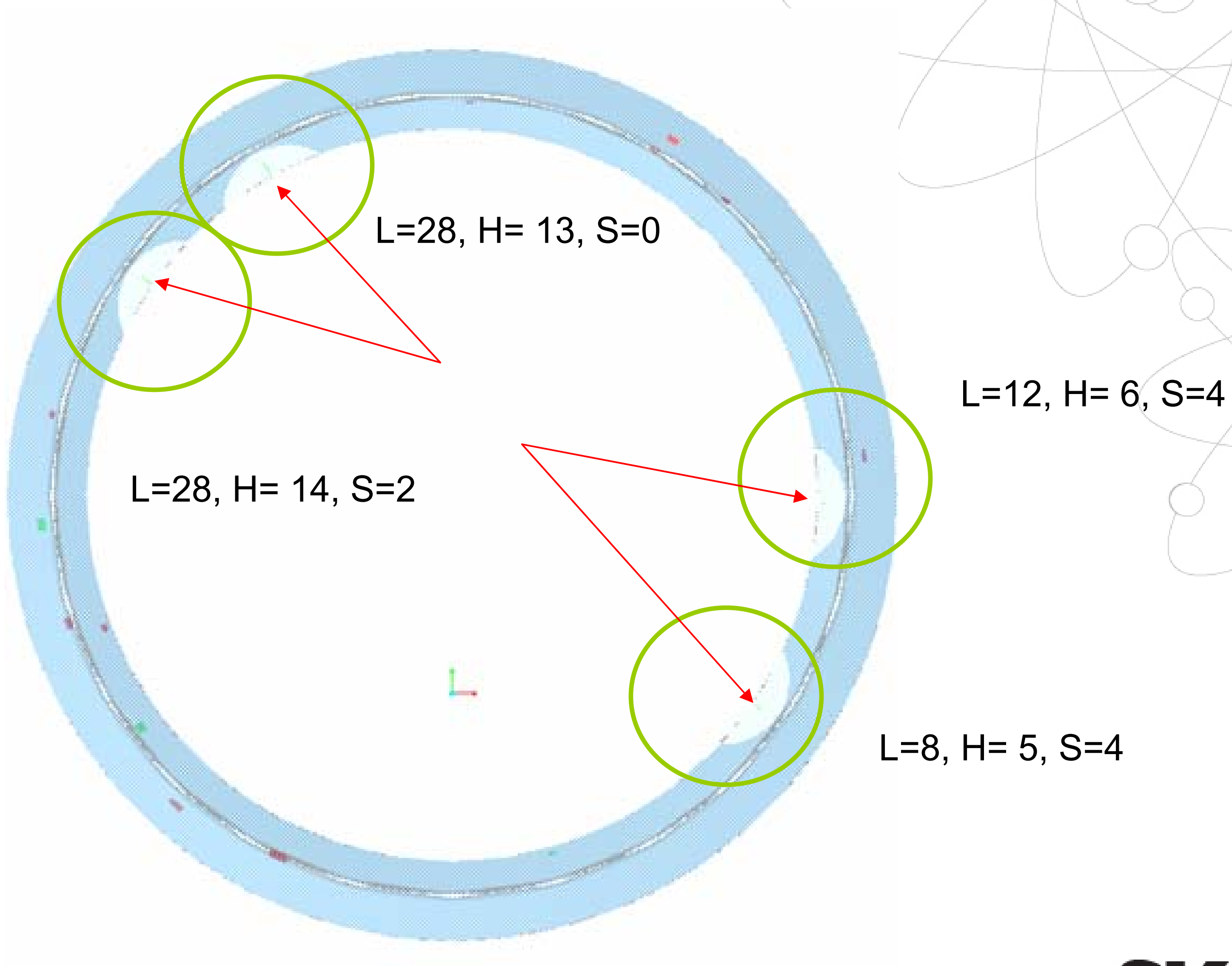
- stop further growth
- metallographic examination

Comparison with inspection results showed that

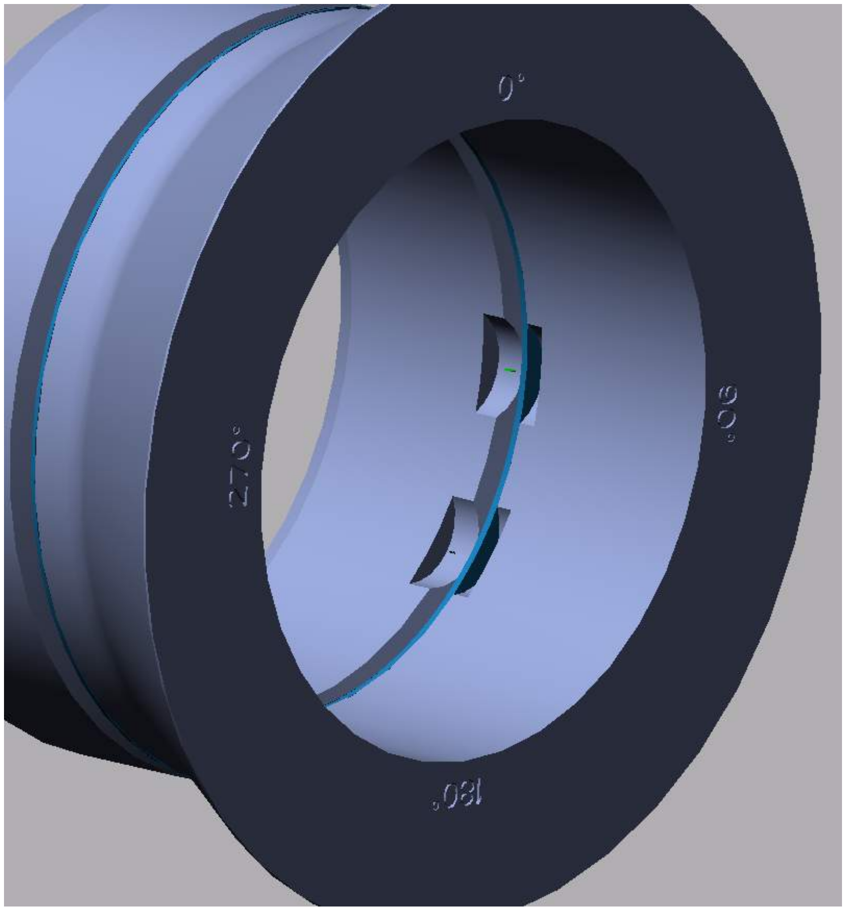
- two of the cracks were under sized
- all cracks were surface breaking

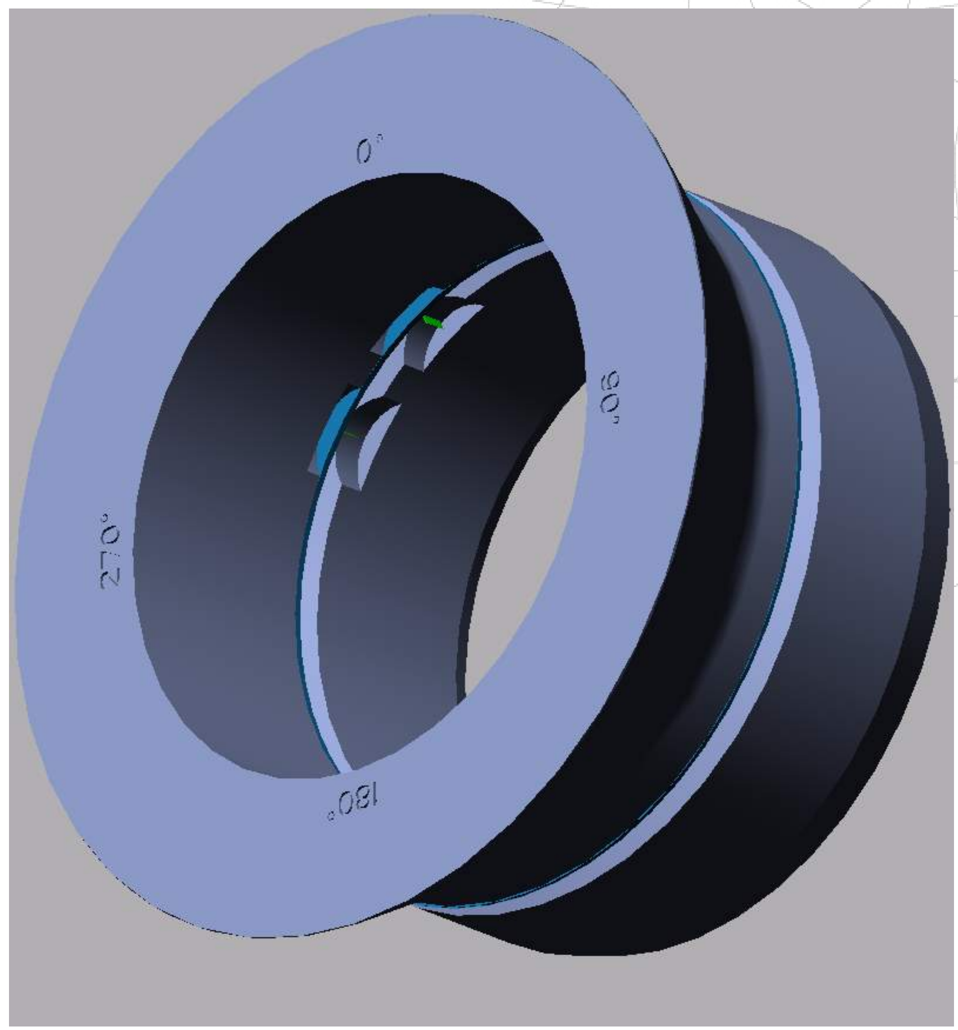


Ringhals 4 outage 2000, 25° outlet nozzle to safe-end weld, UT indications



Removed boat/material samples





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Removed cracks in Ringhals 4, sizing results:

Crack position	Depth acc. to ultrasonic measurements	Depth acc. to destructive examination
91°	10 ± 3 mm	9 ± 1 mm
124°	9 ± 3 mm	6 ± 1 mm
305°	16 ± 3 mm	22 ± 3 mm
330°	13 ±3 mm	22 ± 3 mm

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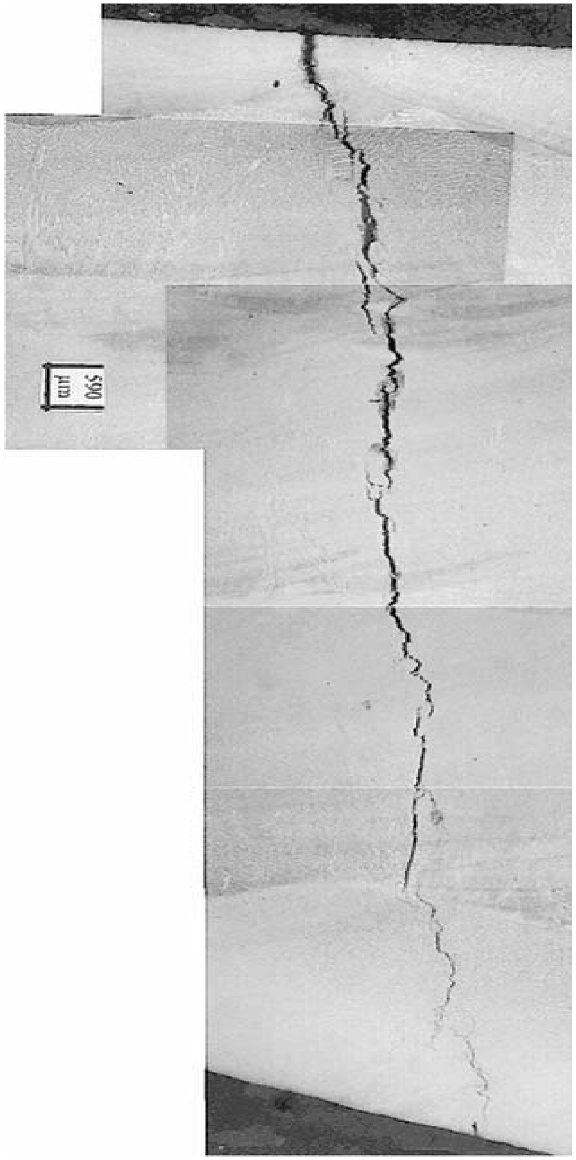
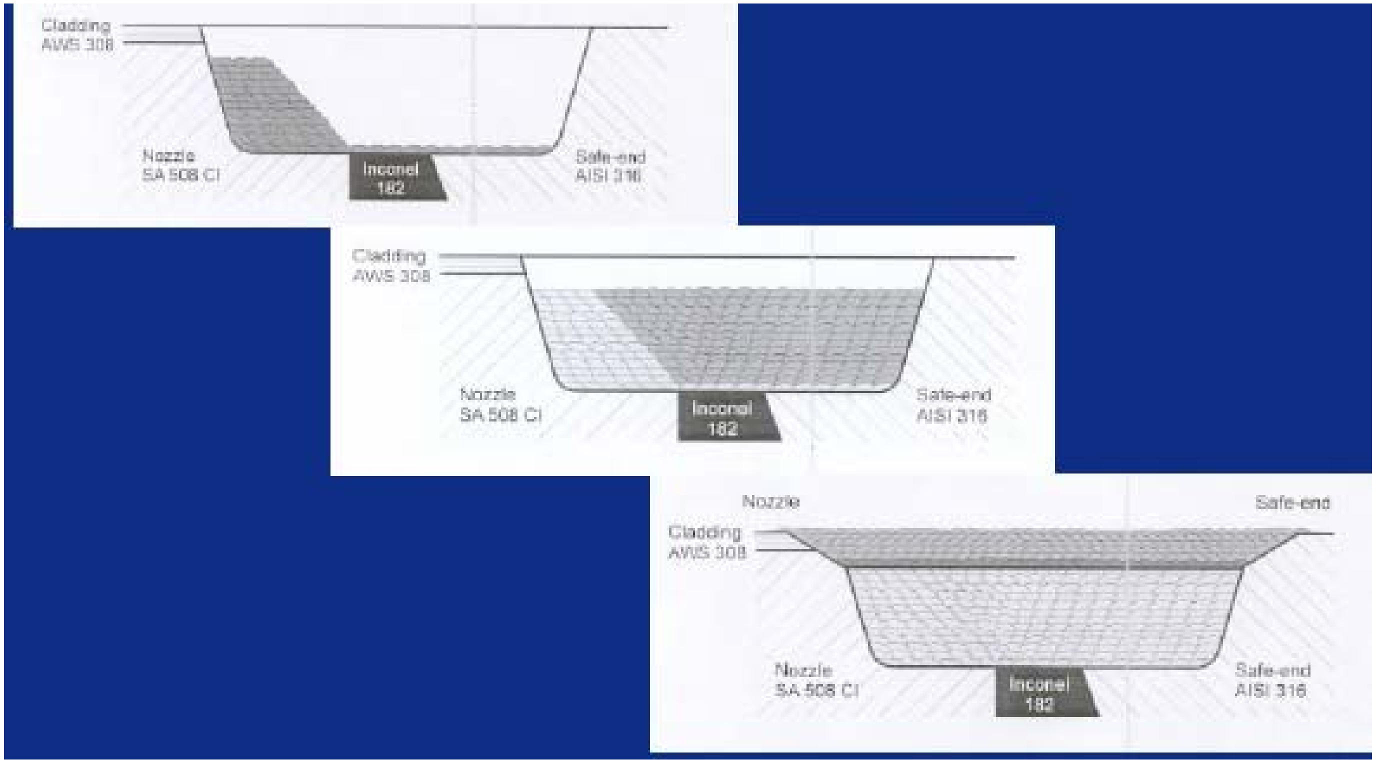
Metallographic examinations



- IDSCC in weld repaired Alloy 182 material
- significant branching of some cracks
- very tight crack tips and also tight crack parts connected to inner surfaces
- some hot cracking and small lack of fusion
- no IDSCC propagation into RPV CS and SS

- Initially, the nozzle was approved for continued operation for another year with follow-up NDE.
- The nozzle was eventually repaired in 2003 through a welding insert using Alloy 52. Duration 46 days at Ringhals 4.

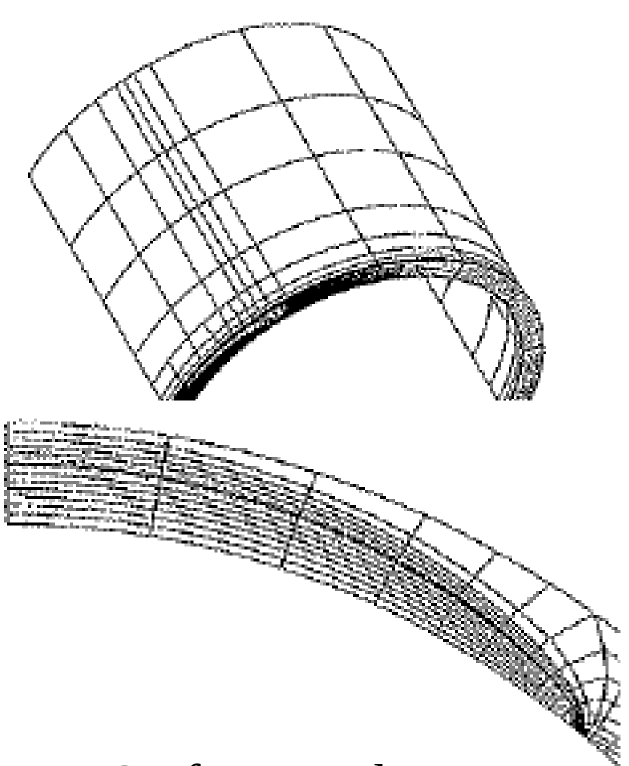


Is it possible to predict the crack growth and to estimate the leak- and rupture probability for pipes containing these kind of cracks?

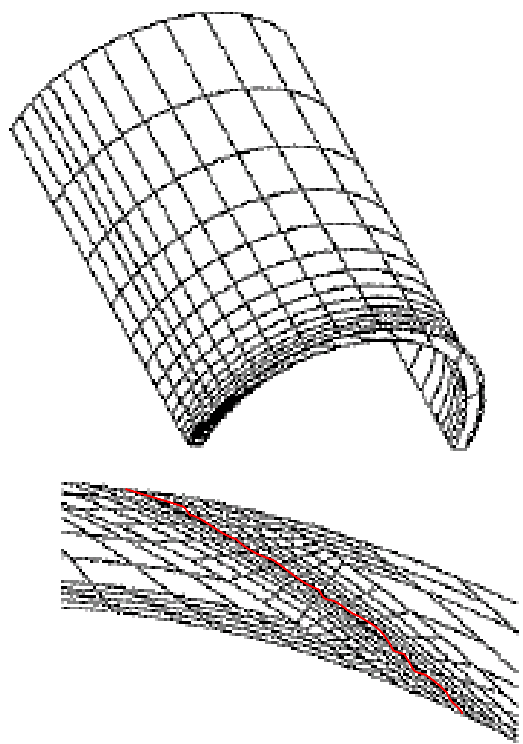
- Deterministic and probabilistic insights

Deterministic insights

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 bending. 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

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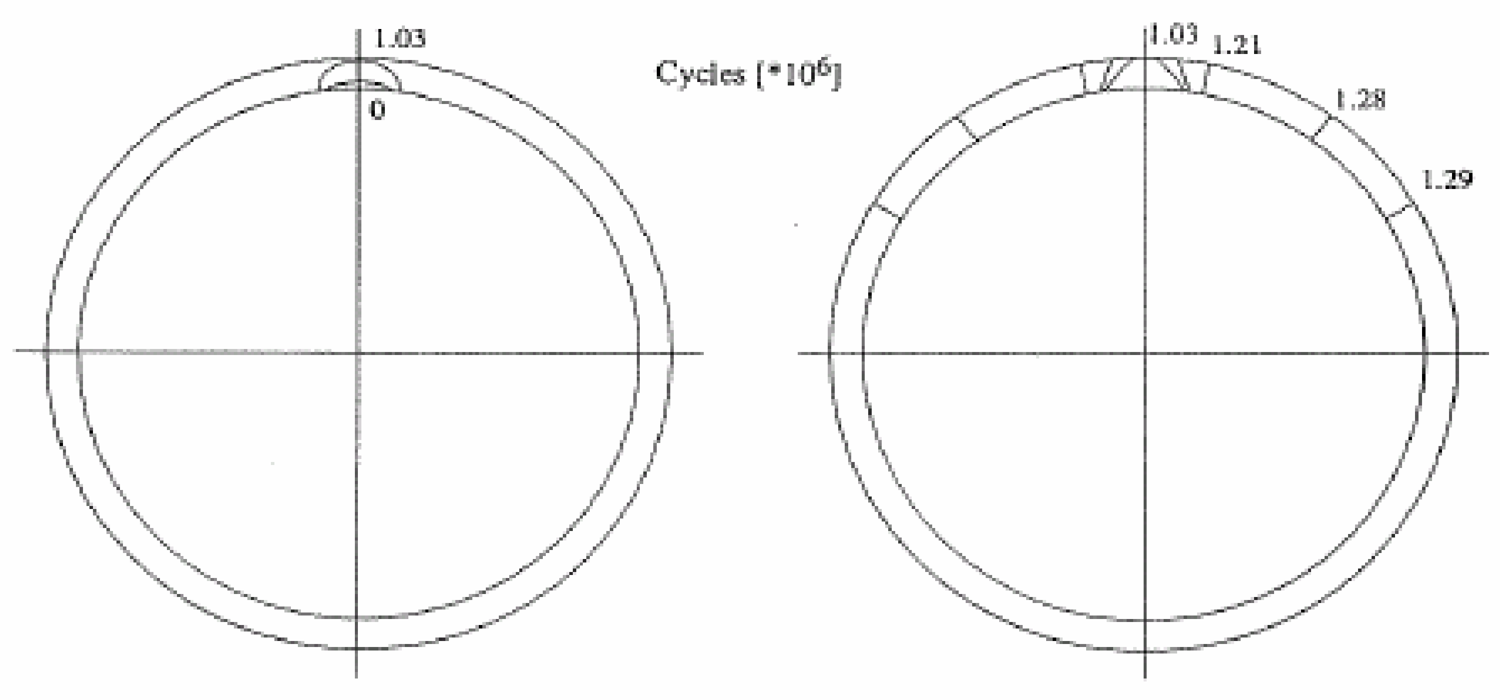
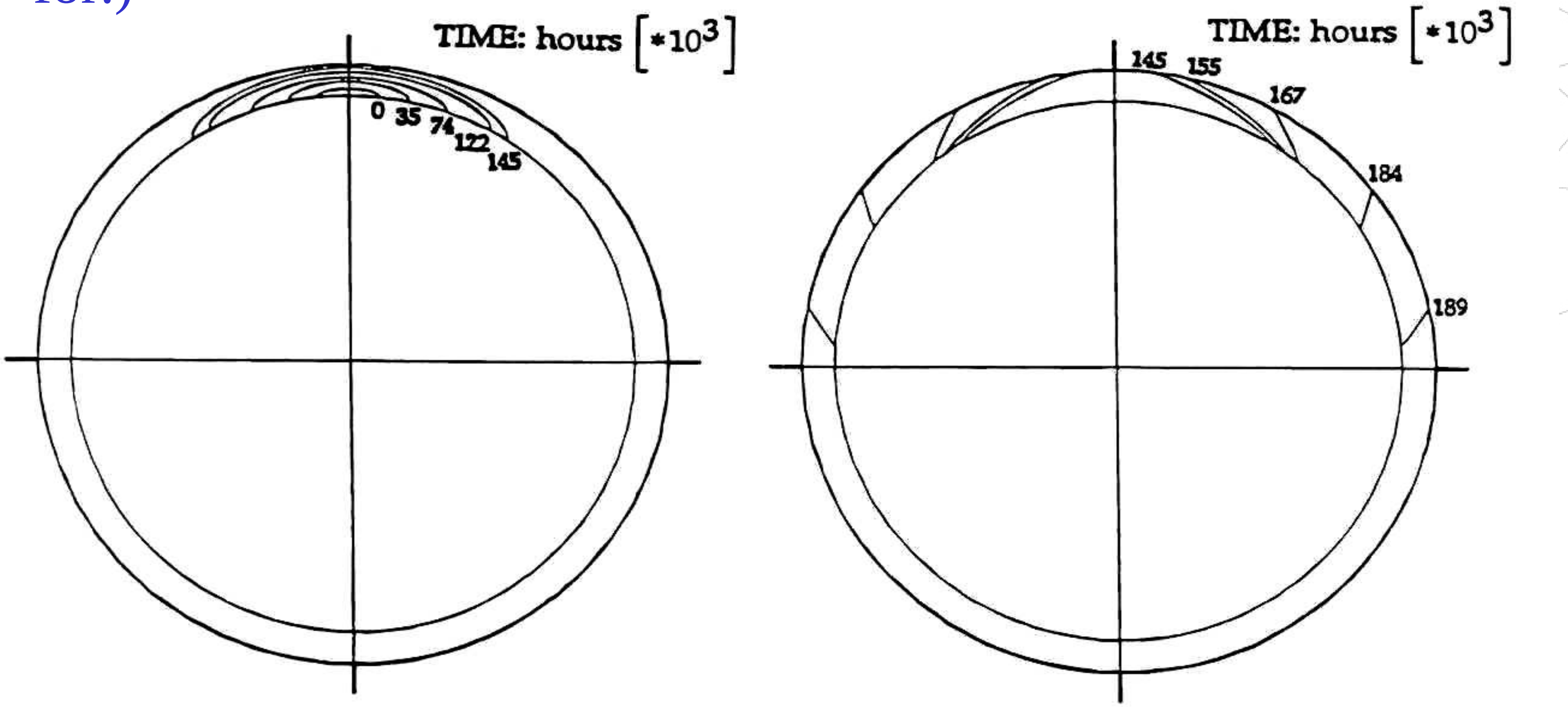
A computer code LBBPIPE was created to predict the crack growth based on the local K-values along the crack front, for either fatigue or stress corrosion. The figures below are an example of how a fatigue crack subjected to high vibration bending stresses will grow to leak and break. (Similar behaviour is obtained for SCC.)



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. (Multiple crack formations are not accounted for.)



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.

LBBPIPE demonstration

Probabilistic insights

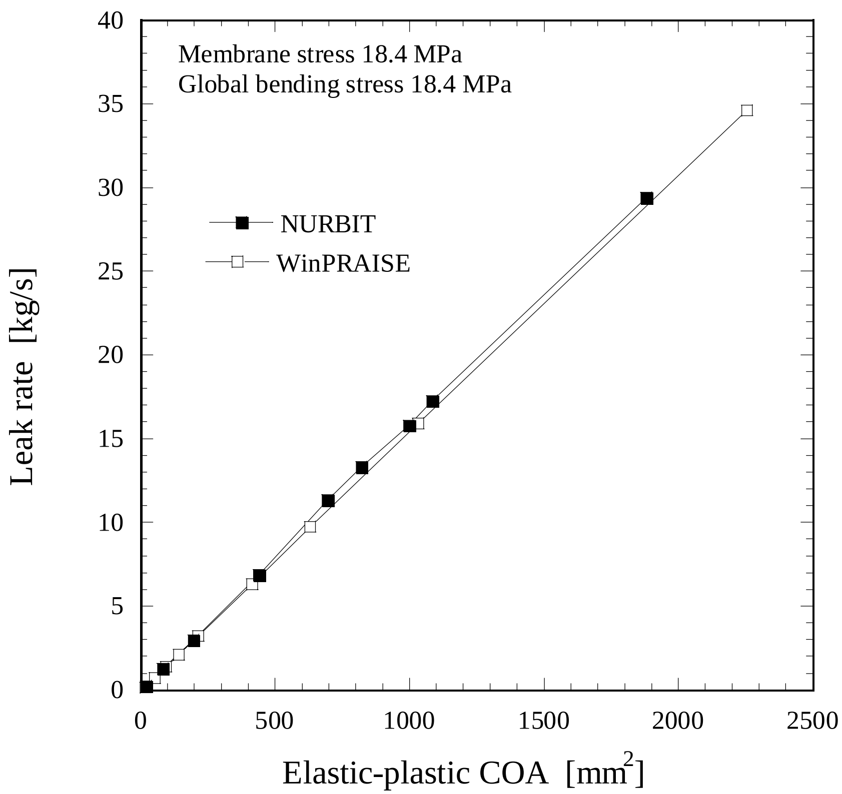
The next step was to include the crack shape predictions into a probabilistic code. The latest code for this purpose is called NURBIT and has been used for RI-ISI pilot studies for Swedish BWR plants. NURBIT has been benchmarked against WinPRAISE within the EU-sponsored project NURBIM.

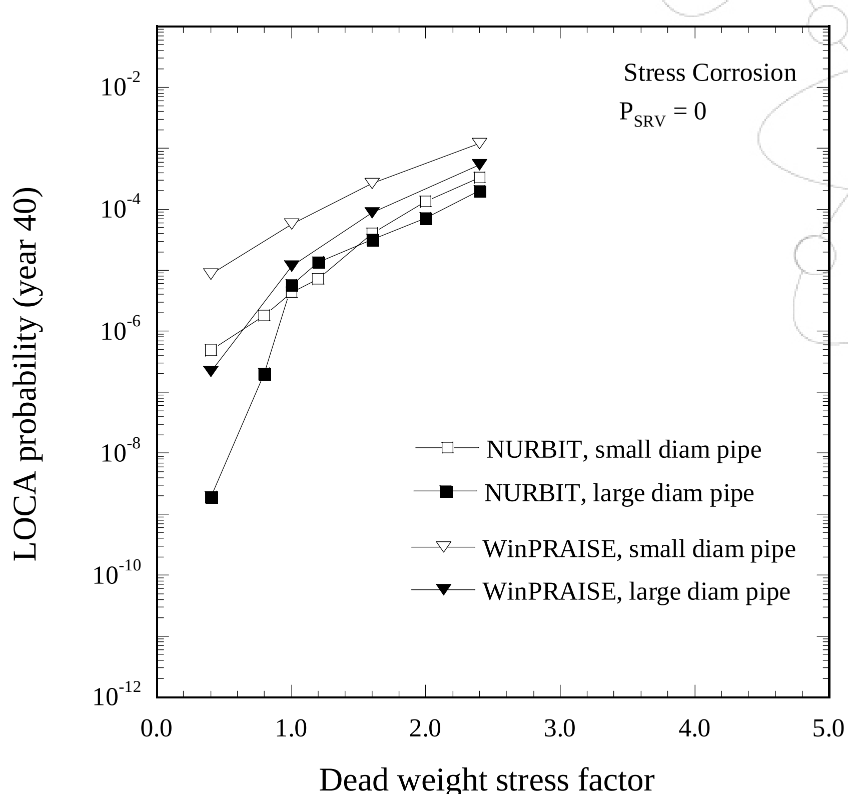
Baseline results for the failure probability after 40 years for SCC in SS pipes

Pipe dimension	**NURBIT** rupture	**WinPRAISE** rupture
Small diameter pipe D = 6.6 inch, t = 0.5 inch	1.152E-4	5.694E-5
Large diameter pipe D = 26.8 inch, t = 1.6 inch	1.800E-5	1.174E-5

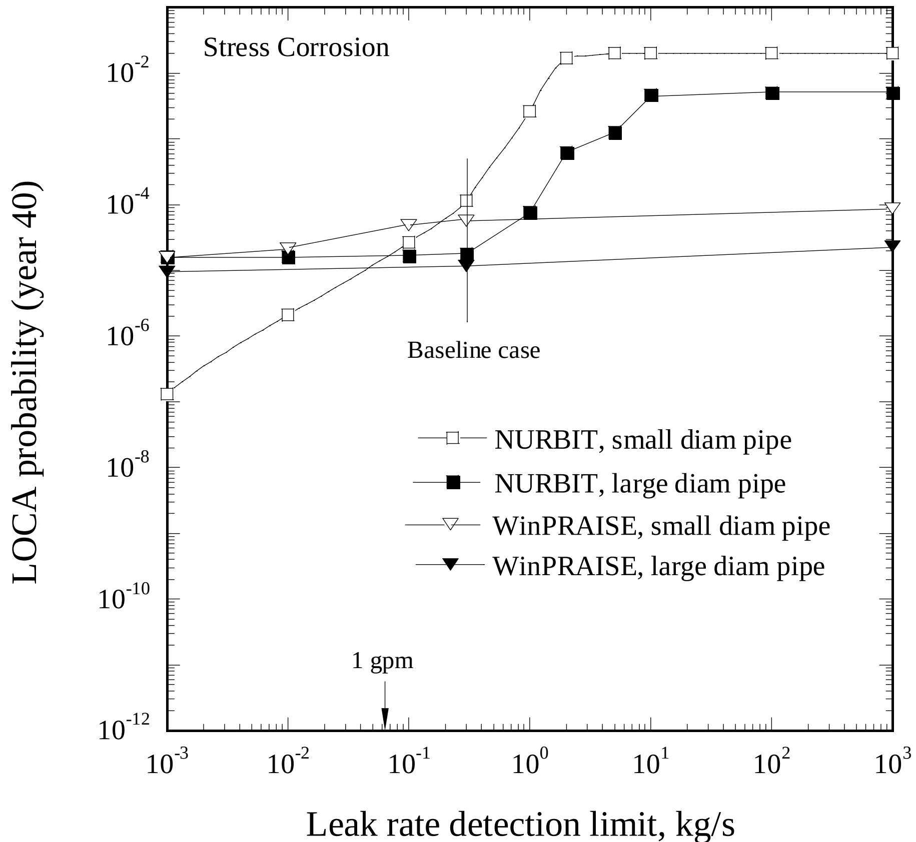
Brickstad, B., Review and benchmarking of Structural Reliability Methods and Associated Software, Appendix A1, SCC benchmark study, 5th Framework of EURATOM, Contract FIKS-CT-2001-00172, 2004.

NURBIT can account for probabilistic leak rate detection and varying inspection intervals. Some results are shown below from the sensitivity analysis of the benchmark study.



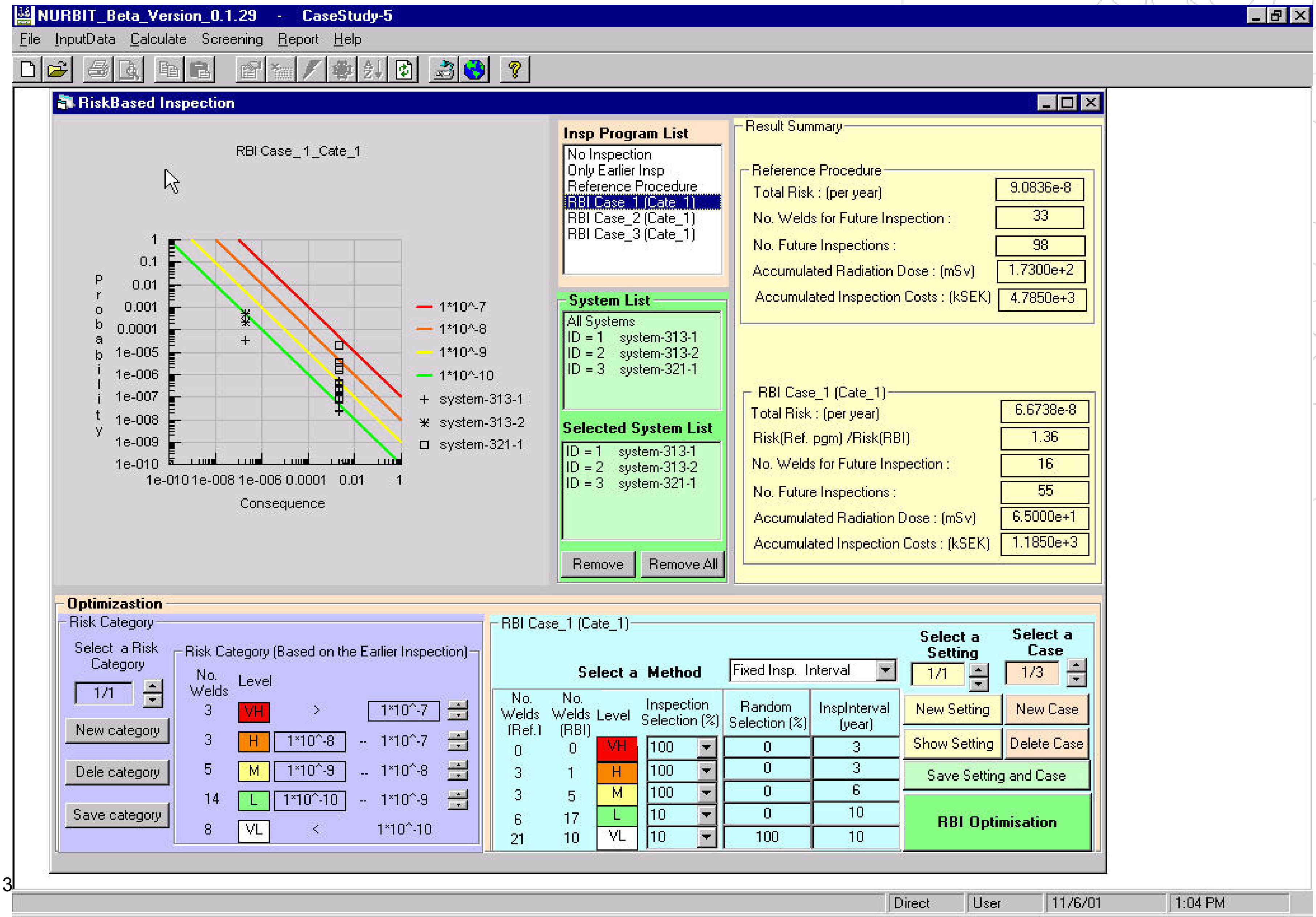


The resulting failure probabilities are in many cases sensitive to the leak detection capabilities. Then features such as complex crack shapes after wall penetration, probabilistic treatment of leak rates and proper J-formulation for the through-wall cracks, are important.



The WinPRAISE results show a much less sensitivity from the leak flow rate detection limit. This is because in this case almost all initial crack sizes will lead to rupture as soon they have grown through the pipe wall. This is not the case with NURBIT. The difference in behaviour is partly due to the simplification in WinPRAISE that at wall penetration the entire length of the surface crack is assumed as the through-wall crack length.

Example of output from the code NURBIT for use in RI-ISI studies



Observations

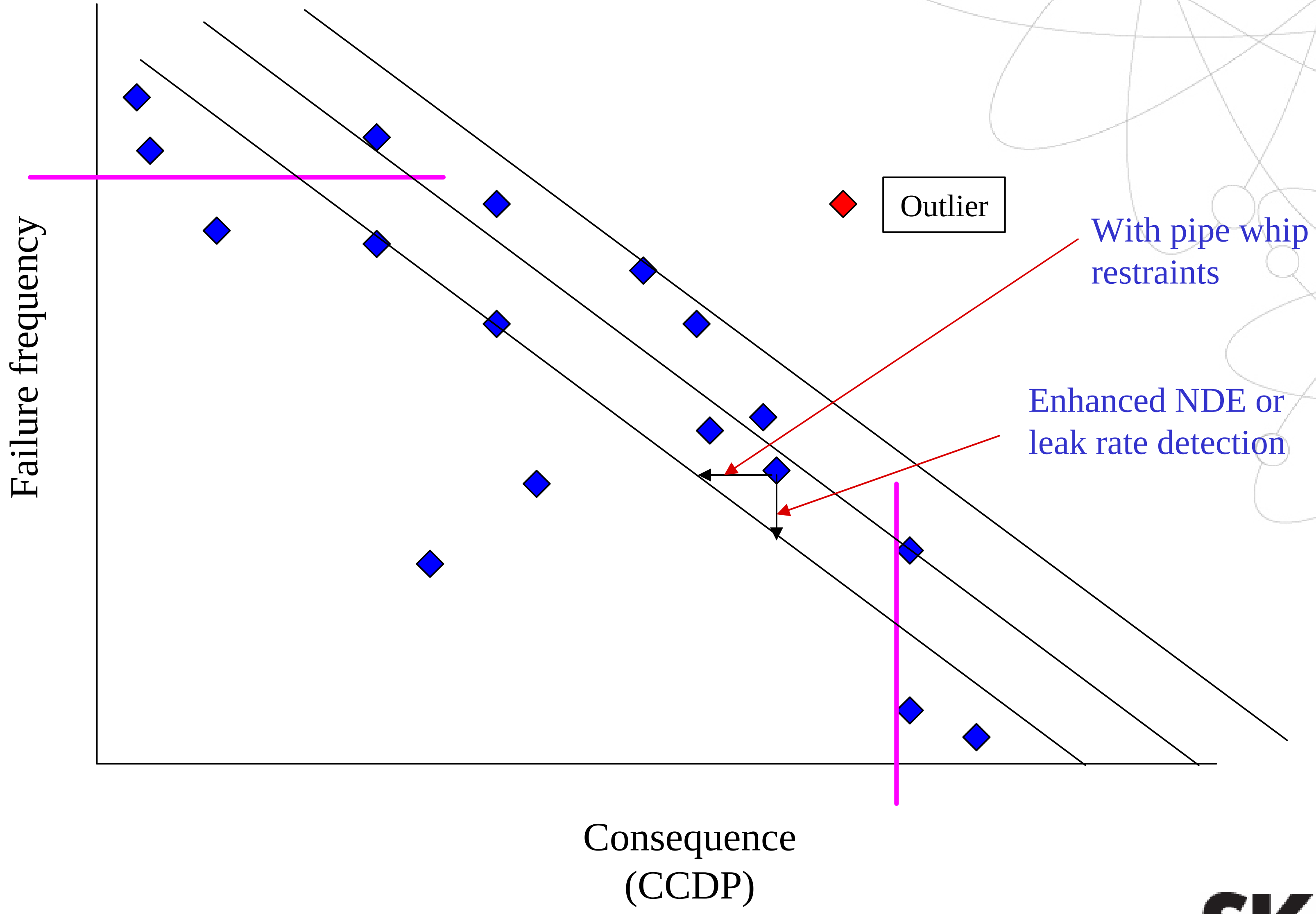
- If an active degradation mechanism exists such as SCC, the resulting leak- and rupture probabilities will be much larger, depending mainly on the stress level and growth rates.
- Also the leak detection flow rate can be very important for the rupture probability. In this context it is important to be able to treat complex crack shapes and to treat the leak flow rate as a probabilistic parameter.
- The tendency for LBB for a pipe with SCC can still be quite small, especially for large diameter pipes. Even for small diameter pipes with SCC, LBB can be fulfilled but then it is even more important to be able to detect small leak flow rates.
- A warning should be issued for large diameter pipes with certain weld residual stress distributions which can cause an initial surface crack to grow to almost a full circumferential crack before wall penetration <u>if</u> growth rates are high.

- However, the SKI staff has not used probabilistic insights in the review of LBB for the Alloy 182 weld connecting the safe-end to the surge line nozzle. At this time SKI is not ready to approve LBB for the surge nozzle Alloy-182 weld.

Future studies/research

- 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.
- Develop a probabilistic LBB-concept based on acceptance criteria for a low p_{break} and for a sufficiently low p_{break}/p_{leak}.
- Often large scatter is observed in SCC-experiments of da/dt versus K. Some results indicate that stress corrosion cracks do not grow such that K will be constant along the crack front. Typically laboratory experiments are made using edge cracked specimens. It would be interesting to perform SCC-experiments on surface cracks to learn more about what really governs the crack growth.

Risk-informed LBB-concept



Laboratory experiments on crack growth rate versus K often show a large scatter. The reasons behind this scatter may not only be explained by different quality of the experiments. Proposed explanations involve influence of wavy crack fronts and different dK/da.