Research

Influence of Crack Morphology on Leak Before Break Margins

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SKi

SKI Perspective

Background

The SKI regulation SKIFS 2004:2 allows for the use of Leak Before Break (LBB) as one way to provide assurance that adequate protection exists against the local dynamic consequences of a pipe break. The way to demonstrate that LBB prevails relies on a deterministic procedure for which a leakage crack is postulated in certain sections of the pipe based on the leak detection capability of the plant. It shall then be demonstrated that certain margins exist against the critical crack length at which a pipe break can be expected. It is well-known that the crack morphology has a large influence on the leakage flow rate and hence on the LBB-margins. SKI has therefore initiated a project to investigate the influence of the crack morphology on LBB-margins applied on pipe systems in a Swedish PWR-plant.

Purpose

The purpose of the project is to evaluate the deterministic LBB-margins for different pipe systems in a Swedish PWR-plant and using different crack morphology parameters.

Results

- The influence of crack morphology on Leak Before Break (LBB) margins is studied. The subject of the report is a number of LBB-submittals to SKI where deterministic LBB-margins are reported. These submittals typically uses a surface roughness of 0.0762 mm (300 microinch) and number of turns equal to zero and an in-house code for the leak rate evaluations. The present report has shown that these conditions give the largest LBB-margins both in terms of the quotient between the critical crack length and the leakage crack size and for the leak rate margin.

- 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, using 1 gpm as the reference leak rate detection limit, are below the safety factor of 2 on crack size and 10 on leak rate, which is generally required for LBB approval.

- The effect of including weld residual stresses on the LBB margins is also investigated. It is shown that for the two examples studied, weld residual stresses were important for the small diameter thin wall pipe whereas it was negligible for the large diameter thick wall pipe which had a self-balanced weld residual stress distribution.

Effect on SKI supervisory and regulatory task

The results of this project will be of a direct use to SKI in the review of applications from Swedish Nuclear Power Plants to use the LBB concept.

Project information

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1 INTRODUCTION

In general the required margin for LBB-applications is a factor of 2.0 between the critical crack and the leakage crack size. In addition there should be a margin of 10 between the installed leak rate detection and the postulated leak rate for evaluation of the leakage crack size. For 1 gpm (0.06308 kg/s) installed leak rate detection means a postulated leak rate of 10 gpm.

Therefore two different through the wall crack sizes need to be determined in a Leak Before Break (LBB) application. One is the crack size when the leakage rate reaches to 10 gpm and the other is the critical crack size.

In the present study, the program NURBIT [1] is used to calculate the crack opening displacement (COD). NURBIT is a computer program in which COD is calculated as a part of solutions (see Appendix 1 for a short description of NURBIT). The program SQUIRT [2] is employed to evaluate leakage rate and the program ProSACC [11] (see Appendix 2 for a short description of the program) is utilized to determine the critical crack sizes.

The results in the present study can be used to verify LBB applications.

This is the second revision of the report. It is found out that the stress intensity factor solutions implemented in SACC [3] are only valid for thin wall pipe. A general 3D finite element calculation was performed in [12]. The solutions in [12] are valid for any kinds of pipes. These solutions are implemented in ProSACC [11] which is in the presented revision used to calculate the critical crack sizes. The differences between the results by SACC and by ProSACC are illustrated in Fig. 1. The input data to generate the results in Fig. 1 are for W5 in main coolant loops (see Section 3).
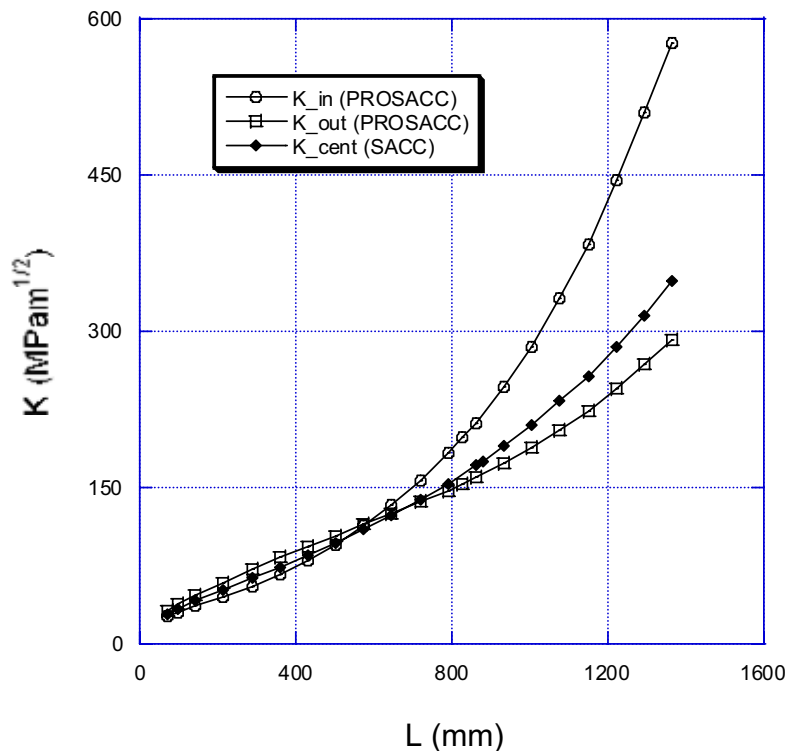

Figure 1. The stress intensity factor as function of crack length for a circumferential through-wall crack, generated by the programs SACC [3] and ProSACC [11].

2 EVALUATION OF LEAKAGE RATE

In SQUIRT, the crack morphology parameters may depend on COD. In this case, the parameter of surface roughness, Path Loss Coefficient (PLC is defined as the number of turns the flow has to make on its way through the crack) and effective wall thickness are calculated by the following equations.

$$
\mu = \begin{cases} \mu_L & , 0.0 \leq COD/\mu_G < 0.1 \\ \mu_L + \dfrac{\mu_G - \mu_L}{4.9}\left(COD/\mu_G - 0.1\right), & 0.1 \leq COD/\mu_G < 5. \\ \mu_G & , COD/\mu_G > 5. \end{cases} \tag{1}
$$

$$
\eta = \begin{cases} \eta_L & , 0.0 \leq COD/\mu_G < 0.1 \\ \eta_L - \dfrac{0.9*\eta_L}{4.9}\left(COD/\mu_G - 0.1\right) & , 0.1 \leq COD/\mu_G < 5. \\ \eta_G & , COD/\mu_G > 5. \end{cases} \tag{2}
$$

$$
\frac{t_e}{t} = \begin{cases} K_L & , 0.0 \leq COD/\mu_G < 0.1 \\ K_L + \dfrac{K_G - K_L}{4.9}\left(COD/\mu_G - 0.1\right) & , 0.1 \leq COD/\mu_G < 5. \\ K_G & , COD/\mu_G > 5. \end{cases} \tag{3}
$$

In Eqn (1-3), μ_L is the local surface roughness, μ_G the global surface roughness, K_L the local crack depth coefficient, K_G the global crack depth coefficient and η_L the local PLC. The crack morphology parameters used in the present study are listed in Table 2.1.

According to the recommendation from [2], crack morphology parameters will be COD independent when $COD/\mu_G > 10$. The analysis in [9] shows that once the COD was about twice the global roughness, global crack morphology parameters can be used in the analysis. In the present analysis, however the global crack morphology parameters will be applied when COD is five times the global roughness (see Eqn (1-3)). It will be shown in the later sections that most COD for the leakage cracks are larger than five times of global roughness. Thus the global crack morphology parameters are used for most leakage cracks calculated in the present study.

Table 2.1 Crack morphology parameters.

Crack morphology	Global surface roughness μ_G (mm)	Local surface roughness μ_L (mm)	Global PLC η_G (Vel. Heads/mm)	Local PLC η_L (Vel. Heads/mm)	Global thickness parameter K_G	Local thickness parameter K_L
Applicant	0.00762	0.00762	0	0	1	1
Fatigue	0.0405	0.00405	0.673	6.73	1.06	1.02
PWSCC	0.1139	0.01139	0.594	5.94	1.33	1.07

3   MAIN COOLANT LOOPS

3.1   Input data

The input data are taken from [4] and listed in Tables 3.1-3.3. In the evaluation of the critical crack size using the R6 method in ProSACC, it is assumed that the membrane stress is a primary stress whereas half of the bending stress is a primary stress and the other half is a secondary stress.

Table 3.1 Material Properties (for 288 °C and 323 °C)

Yield Strength (MPa)	Ultimate Strength (MPa)	J_C (kN/m)	K_C (MPa√m)
162	365.6	357.5	265.9

Note: Fracture Toughness is based on mean J_R-curve for austenitic stainless steel weld SMAW after 2 mm crack extension. The data is taken from [10].

Table 3.2 Pipe Geometry

Weld Location	Out diameter (mm)	Wall thickness (mm)
W1	871.5	64.85
W5	946.2	76.8

Table 3.3 Loads on the welds

Weld Location	Pressure (MPa)	T (°C)	Normal Condition		Faulted Condition	
			Membrane (MPa)	Bending (MPa)	Membrane (MPa)	Bending (MPa)
W1	15.5	323	40.4	51.1	44.8	89.7
W5	15.5	288	36.6	6.5	39	43.3

3.2   Results

In the following, crack length in the middle of the pipe wall thickness is defined as the average crack length. The margin is the ratio between the critical crack size and the leakage crack size. Three different cases are studied. These cases are defined in Table 3.4. The results are shown in Tables 3.5-3.8. It is noted that the applicant critical crack size is determined by limit load analysis.

Table 3.4 Analysis cases.

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

Table 3.5 Average leakage crack size.

Location	Applicant (mm)	Case 1 (mm)	Case 2 (mm)
W1	131.3	174.4	238.4
W5	221.0	236.4	311.4

Table 3.6 Crack length margins (using Applicant critical crack size).

Location	Applicant critical crack size (mm)	Average critical crack size by ProSACC (mm)	Margin for Case 1	Margin for Case 2	Leakage rate for Case 3 (GPM)
W1	531	577.4	3.05	2.23	13.77
W5	876	827.4	3.71	2.81	28.61

Table 3.7 Crack length margins (using critical crack size by ProSACC).

Location	Applicant critical crack size (mm)	Average critical crack size by ProSACC (mm)	Margin for Case 1	Margin for Case 2	Leakage rate for Case 3 (gpm)
W1	531	577.4	3.31	2.42	17.15
W5	876	827.4	3.50	2.66	23.78

Table 3.8 COD by NURBIT and leakage rate by SQUIRT

Location	Case 1			Case 2		
	COD_{in} (mm)	COD_{out} (mm)	Leakage rate (gpm)	COD_{in} (mm)	COD_{out} (mm)	Leakage rate (gpm)
W1	0.168	0.234	10.11	0.254	0.360	9.86
W5	0.114	0.160	9.97	0.167	0.239	10.13

4   SURGE LINE

4.1   Input data

The input data are taken from [5] and listed in Tables 4.1-4.3. In the evaluation of the critical crack size using the R6 method in ProSACC, it is assumed that the membrane stress is a primary stress whereas half of the bending stress is a primary stress and the other half is a secondary stress.

Table 4.1 Material Properties (315 °C)

Yield Strength (MPa)	Ultimate Strength (MPa)	J_C (kN/m)	K_C (MPa√m)
149	451	357.5	265.9

Note: Fracture Toughness is based on mean J_R-curve for austenitic stainless steel weld SMAW after 2 mm crack extension. The data is taken from [10].

Table 4.2 Pipe Geometry

Weld Location	Out diameter (mm)	Wall thickness (mm)
W1	355.6	31.8
W2	355.6	31.8
W4	355.6	31.8

Table 4.3 Loads on the welds

Weld Location	Pressure (MPa)	T (°C)	Normal Condition		Faulted Condition	
			Membrane (MPa)	Bending (MPa)	Membrane (MPa)	Bending (MPa)
W1	15.5	323	30.9	67.2	32.1	132.9
W2	15.5	323	32.1	18.9	32.5	57.2
W4	15.5	323	32.2	44.6	33.0	110.6

4.2 Results

In the following, crack length in the middle of the pipe wall thickness is defined as the average crack length. The margin is the ratio between the critical crack size and the leakage crack size. Three different cases are studied. These cases are defined in Table 4.4. The results are shown in Tables 4.5-4.8.

Table 4.4 Analysis cases.

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

Table 4.5 Average leakage crack size.

Location	Applicant (mm)	Case 1 (mm)	Case 2 (mm)
W1	103.1	130.7	167.6
W2	153.2	175.5	218.3
W4	123.2	148.7	187.5

Table 4.6 Crack length margins (using Applicant critical crack size).

Location	Applicant critical crack size (mm)	Average critical crack size by ProSACC (mm)	Margin for Case 1	Margin for Case 2	Leakage rate for Case 3 (gpm)
W1	291.1	241.7	2.23	1.74	6.09
W2	423.2	335.5	2.41	1.94	9.23
W4	323.6	264.6	2.18	1.73	6.11

Table 4.7 Crack length margins (using critical crack size by ProSACC).

Location	Applicant critical crack size (mm)	Average critical crack size by ProSACC (mm)	Margin for Case 1	Margin for Case 2	Leakage rate for Case 3 (gpm)
W1	291.1	241.7	1.85	1.44	2.81
W2	423.2	335.5	1.91	1.54	2.85
W4	323.6	264.6	1.78	1.41	2.37

Table 4.8 COD by NURBIT and leakage rate by SQUIRT

Location	Case 1			Case 2		
	COD_{in} (mm)	COD_{out} (mm)	Leakage rate (gpm)	COD_{in} (mm)	COD_{out} (mm)	Leakage rate (gpm)
W1	0.164	0.243	10.01	0.251	0.366	9.70
W2	0.140	0.200	10.27	0.221	0.305	10.32
W4	0.153	0.227	10.31	0.243	0.346	10.24

5 SURGE LINE BIMETALLIC WELD

5.1 Input data

The input data are taken from [6] and listed in Tables 5.1-5.3. In the evaluation of the critical crack size using the R6 method in ProSACC, it is assumed that the membrane stress is a primary stress whereas half of the bending stress is a primary stress and the other half is a secondary stress.

Table 5.1 Material Properties (315 °C)

Yield Strength (MPa)	Ultimate Strength (MPa)	J_C (kN/m)	K_C (MPa√m)
354	561	785.3	394.1

Note: Fracture Toughness is based on mean J_R-curve for Inconel 182 after 2 mm crack extension (E=180 GPa). The data is taken from [10].

Table 5.2 Pipe Geometry

Weld Location	Out diameter (mm)	Wall thickness (mm)
Bimetallic weld	386	42

Table 5.3 Loads on the welds

Weld Location	Pressure (MPa)	T (°C)	Normal Condition		Faulted Condition	
			Membrane (MPa)	Bending (MPa)	Membrane (MPa)	Bending (MPa)
Bimetallic weld	15.5	345	24.50	30.42	24.85	101.26

5.2 Results

In the following, crack length in the middle of the pipe wall thickness is defined as the average crack length. The margin is the ratio between the critical crack size and the leakage crack size. Three different cases are studied. These cases are defined in Table 5.4. The results are shown in Tables 5.5-5.8.

Table 5.4 Analysis cases.

Case	Crack morphology	Leakage crack size
1	Applicants	Leakage is 10 gpm
2	Fatigue	Leakage is 10 gpm
3	Fatigue	Calculate the leakage rate when the leakage crack size is one half of the critical crack size
4	PWSCC	Leakage is 10 gpm
5	PWSCC	Calculate the leakage rate when the leakage crack size is one half of the critical crack size

Table 5.5 Average leakage crack size.

Location	Applicant (mm)	Case 1 (mm)	Case 2 (mm)	Case 4 (mm)
Bimetallic weld	172.7	157.6	208.8	214.3

Table 5.6a Crack length margins (using Applicant critical crack size).

Location	Applicant critical crack size (mm)	Average critical crack size by ProSACC (mm)	Margin for Case 1	Margin for Case 2	Leakage rate for Case 3 (gpm)
Bimetallic weld	472.4	438.4	3.00	2.26	15.92

Table 5.6b Crack length margins (using Applicant critical crack size).

Location	Applicant critical crack size (mm)	Average critical crack size by ProSACC (mm)	Margin for Case 4	Leakage rate for Case 5 (gpm)
Bimetallic weld	472.4	438.4	2.20	15.38

Table 5.7a Crack length margins (using critical crack size by ProSACC).

Location	Applicant critical crack size (mm)	Average critical crack size by ProSACC (mm)	Margin for Case 1	Margin for Case 2	Leakage rate for Case 3 (gpm)
Bimetallic weld	472.4	438.4	2.78	2.10	12.46

Table 5.7b Crack length margins (using critical crack size by ProSACC).

Location	Applicant critical crack size (mm)	Average critical crack size by ProSACC (mm)	Margin for Case 4	Leakage rate for Case 5 (gpm)
Bimetallic weld	472.4	438.4	2.05	11.73

Table 5.8a COD by NURBIT and leakage rate by SQUIRT

Location	Case 1			Case 2		
	COD_{in} (mm)	COD_{out} (mm)	Leakage rate (gpm)	COD_{in} (mm)	COD_{out} (mm)	Leakage rate (gpm)
Bimetallic weld	0.178	0.276	10.03	0.303	0.448	10.67

Table 5.8b COD by NURBIT and leakage rate by SQUIRT

Location	Case 4		
	COD_{in} (mm)	COD_{out} (mm)	Leakage rate (gpm)
Bimetallic weld	0.319	0.470	10.70

6 RESIDUAL HEAT REMOVAL LINES

6.1 Input data

The input data are [7] and listed in Tables 6.1-6.3. In the evaluation of the critical crack size using the R6 method in ProSACC, it is assumed that the membrane stress is a primary stress whereas half of the bending stress is a primary stress and the other half is a secondary stress.

Table 6.1 Material Properties (323 °C)

Yield Strength (MPa)	Ultimate Strength (MPa)	J_C (kN/m)	K_C (MPa√m)
143	495	357.5	265.9

Note: Fracture Toughness is based on mean J_R-curve for austenitic stainless steel weld SMAW after 2 mm crack extension. The data is taken from [10].

Table 6.2 Pipe Geometry

Weld Location	Out diameter (mm)	Wall thickness (mm)
L1W1	323.8	27.13
L1W2	323.9	29.16
L2W1	323.8	27.13
L2W2	323.9	29.16
L2W3	323.9	29.16

Table 6.3. Loads on the welds

Weld Location	Pressure (MPa)	T (°C)	Normal Condition		Faulted Condition	
			Membrane (MPa)	Bending (MPa)	Membrane (MPa)	Bending (MPa)
L1W1	15.5	323	35.1	6.2	35.9	40.5
L1W2	15.5	323	31.8	6.8	32.6	33.3
L2W1	15.5	323	34.5	63.8	36.9	119.5
L2W2	15.5	323	31.3	56.8	33.5	102.2
L2W3	15.5	323	31.6	54.9	33.4	95.4

6.2 Results

In the following, crack length in the middle of the pipe wall thickness is defined as the average crack length. The margin is the ratio between the critical crack size and the leakage crack size. Three different cases are studied. These cases are defined in Table 6.4. The results are shown in Tables 6.5-6.8.

Table 6.4 Analysis cases.

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

Table 6.5 Average leakage crack size.

Location	Applicant (mm)	Case 1 (mm)	Case 2 (mm)
L1W1	158.8	176.4	212.6
L1W2	166.1	182.4	222.6
L2W1	89.2	122.1	155.7
L2W2	99.0	131.0	164.0
L2W3	100.6	131.2	165.7

Table 6.6 Crack length margins (using Applicant critical crack size).

Location	Applicant critical crack size (mm)	Critical crack size by ProSACC (mm)	Margin for Case 1	Margin for Case 2	Leakage rate for Case 3 (gpm)
L1W1	405.4	317.7	2.30	1.91	8.24
L1W2	426.5	335.9	2.34	1.92	8.88
L2W1	278.9	222.4	2.28	1.79	7.06
L2W2	310.3	246.7	2.37	1.89	8.13
L2W3	320.3	254.2	2.44	1.93	8.79

Table 6.7 Crack length margins (using critical crack size by ProSACC).

Location	Applicant critical crack size (mm)	Average critical crack size by ProSACC (mm)	Margin for Case 1	Margin for Case 2	Leakage rate for Case 3 (gpm)
L1W1	405.4	317.7	1.80	1.49	2.19
L1W2	426.5	335.9	1.84	1.51	2.30
L2W1	278.9	222.4	1.82	1.43	2.75
L2W2	310.3	246.7	1.88	1.50	3.09
L2W3	320.3	254.2	1.94	1.53	3.43

Table 6.8 COD by NURBIT and leakage rate by SQUIRT

Location	Case 1			Case 2		
	COD_{in} (mm)	COD_{out} (mm)	Leakage rate (gpm)	COD_{in} (mm)	COD_{out} (mm)	Leakage rate (gpm)
L1W1	0.137	0.191	10.44	0.212	0.287	10.12
L1W2	0.133	0.186	10.04	0.218	0.294	10.60
L2W1	0.167	0.247	10.18	0.261	0.378	10.15
L2W2	0.160	0.239	10.05	0.249	0.361	9.76
L2W3	0.157	0.235	9.82	0.250	0.362	9.90

It is observed in Table 6.7 that Weld L2W1 has a lower margin in comparison with weld L1W1. However, the leakage rate for L2W1 is higher in Case 3. This can be explained by the fact that L2W1 has a much higher bending stress during the operation (63.8 MPa for L2W1 and 6.8 MPa for L1W1). As a result, the leakage rate for L2W1 will be increased much faster with increasing crack length (see also Fig. 2).
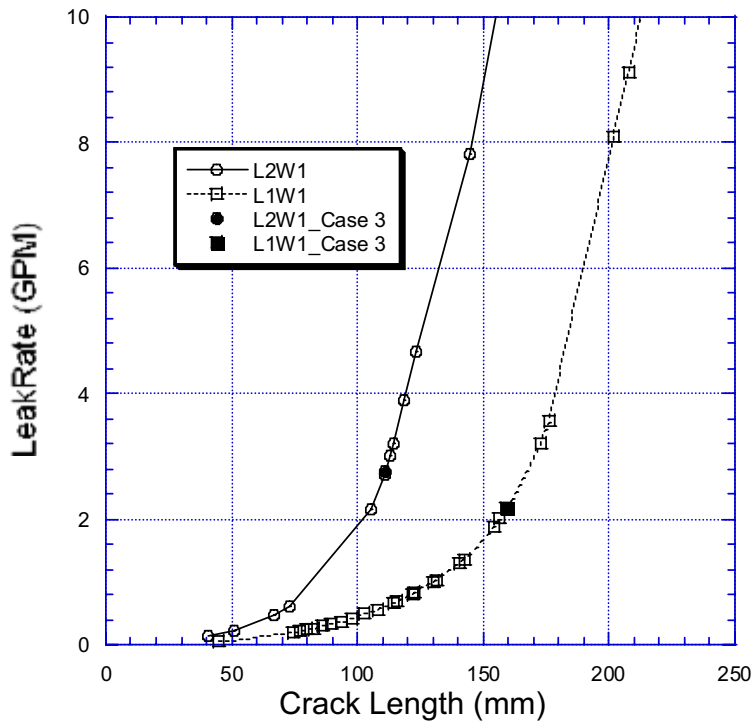
Figure 2. Leakage rate as function of crack length for weld L1W1 and L2W1 in the residual heat removal lines.

7   ACCUMULATOR LINES

7.1   Input data

The input data are taken from [8] and listed in Tables 7.1-7.3. In the evaluation of the critical crack size using the R6 method in ProSACC, it is assumed that the membrane stress is a primary stress whereas half of the bending stress is a primary stress and the other half is a secondary stress.

Table 7.1 Material Properties

Yield Strength (MPa)		Ultimate Strength (MPa)		J_C (kN/m)		K_C (MPa√m)	
21 °C	288 °C	21 °C	288 °C	21 °C	288 °C	21 °C	288 °C
227	137	537	514	621.4	357.5	373.2	265.9

Note: Fracture Toughness is based on mean J_R-curve for austenitic stainless steel weld SMAW after 2 mm crack extension. The data is taken from [10].

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Table 7.2 Pipe Geometry

Weld Location	Out diameter (mm)	Wall thickness (mm)
L1W6	324.0	29.2
L1W12	324.0	29.2
L2W1	323.8	29.7
L2W13	324.0	29.2
L3W14	324.0	29.2
L3W21	323.8	8.3

Table 7.3 Loads on the welds

Weld Location	Pressure (MPa)	T (°C)	Normal Condition		Faulted Condition	
			Membrane (MPa)	Bending (MPa)	Membrane (MPa)	Bending (MPa)
L1W6	4.6	21	9.97	24.28	10.81	58.70
L1W12	4.6	21	9.88	10.38	10.73	51.60
L2W1	15.8	288	31.24	28.69	32.90	58.23
L2W13	4.6	21	9.90	11.15	10.60	49.14
L3W14	4.6	21	8.80	42.30	10.61	68.59
L3W21[*]	4.6	21	40.73	63.90	43.82	100.79

[*] Weld L3W21 is also subjected to a local bending welding residual stress (±215 MPa) according to [10].

7.2 Results

In the following, crack length in the middle of the pipe wall thickness is defined as the average crack length. The margin is the ratio between the critical crack size and the leakage crack size. Three different cases are studied. These cases are defined in Table 7.4. The results are shown in Tables 7.5-7.8. It should be pointed out that the operation temperature is 21 °C except L3W21. In the leakage calculation, the fluid temperature is increased to 150 °C to make a saturate mixture. In addition, only one half of the residual stress for L3W21 is applied in determination of the critical crack size to reduce the contribution of the residual stress at rupture.

Table 7.4 Analysis cases.

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

Table 7.5 Average leakage crack size.

Location	Applicant (mm)	Case 1 (mm)	Case 2 (mm)
L1W6	210.6	207.1	250.8
L1W12	260.9	243.1	293.8
L2W1	123.7	139.1	173.9
L2W13	257.3	239.2	290.5
L3W14	174.0	174.7	219.8
L3W21	95.8	137.1	160.4

Table 7.6 Crack length margins (using Applicant critical crack size).

Location	Applicant critical crack size (mm)	Average critical crack size by ProSACC (mm)	Margin for Case 1	Margin for Case 2	Leakage rate for Case 3 (gpm)
L1W6	478.9	448.5	2.31	1.91	8.03
L1W12	494.0	461.8	2.03	1.68	3.32
L2W1	375.1	294.4	2.70	2.16	13.45
L2W13	499.8	>463	2.09	1.72	3.73
L3W14	459.8	431.7	2.63	2.09	12.07
L3W21	346.5	309.1	2.53	2.16	13.40

Table 7.7 Crack length margins (using critical crack size by ProSACC).

Location	Applicant critical crack size (mm)	Average critical crack size by ProSACC (mm)	Margin for Case 1	Margin for Case 2	Leakage rate for Case 3 (gpm)
L1W6	478.9	448.5	2.17	1.79	5.45
L1W12	494.0	461.8	1.90	1.57	2.39
L2W1	375.1	294.4	2.12	1.69	4.69
L2W13	499.8	>463	1.94	1.59	2.58
L3W14	459.8	431.7	2.47	1.96	9.59
L3W21	346.5	309.1	2.25	1.93	8.54

Table 7.8 COD by NURBIT and leakage rate by SQUIRT

Location	Case 1			Case 2		
	COD$_{in}$ (mm)	COD$_{out}$ (mm)	Leakage rate (gpm)	COD$_{in}$ (mm)	COD$_{out}$ (mm)	Leakage rate (gpm)
L1W6	0.128	0.176	10.49	0.203	0.267	10.07
L1W12	0.114	0.151	10.00	0.187	0.237	10.27
L2W1	0.117	0.174	9.90	0.187	0.267	10.08
L2W13	0.114	0.152	10.00	0.187	0.238	10.11
L3W14	0.142	0.202	10.03	0.217	0.296	10.03
L3W21	0.276	0.130	10.03	0.335	0.194	10.00

8 INFLUENCE OF WELDING RESIDUAL STRESSES

The welding residual stress was not considered in the previous calculations, except L3W21 in the Accumulator lines. The influence of the welding residual stress is studied by the following two examples.

It should be pointed out that in the following examples the full weld residual stress is accounted for when determining the leakage crack size whereas it is reduced with a factor of 2 when determining the critical crack size. This is to account for the diminishing effect of secondary stresses for ductile materials at high primary loads.

8.1 Weld W2 in Surge Line

As the first example, the input data for W2 in surge line are used. The residual stress recommended in [10] is applied. The distribution of the welding residual stress is plotted in Fig. 3. It is observed that the residual stress is a self balanced stress distribution. The nonlinear weld residual stress distribution is in this case accounted for when determining the COD and the critical crack size

The results of leakage rates with or without residual stress are shown in Fig. 4. A little higher leakage rates are obtained for the case with the residual stress. The crack Opening displacements (COD) in the inside surface and in the outside surface of the crack are plotted in Fig. 5. CODs in the outside surface of the crack are almost the same for both cases, while a larger COD in the inside surface of the crack is obtained for the case with the residual stress. This fact explains a somewhat higher leakage rate for the case with residual stress.

The summarized results are listed in Tables 8.1-8.2. The results without the residual stress are slightly conservative for the present example. However, this should not be considered as a general result even if it is expected that self-balanced weld residual stresses will have a small effect on LBB margins. Other less favourable combinations of loads, residual stress distribution and material data, may have a more substantial effect on the LBB margins.
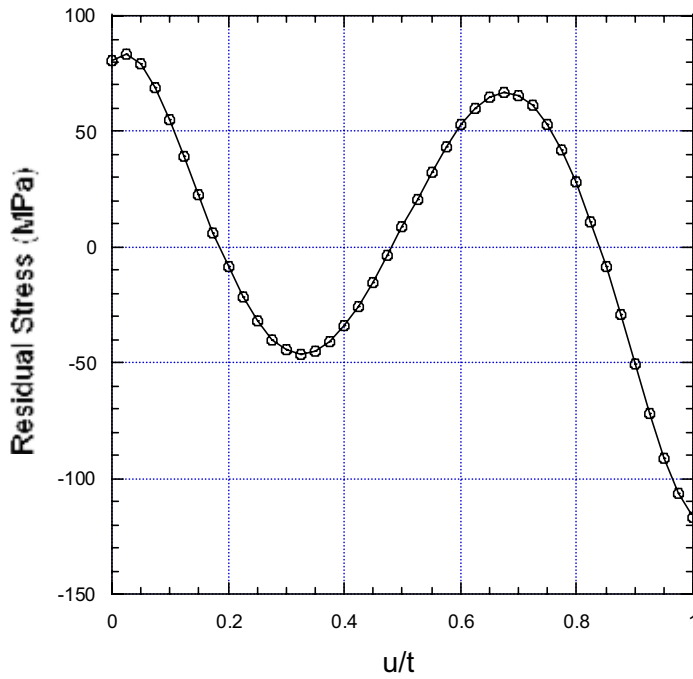
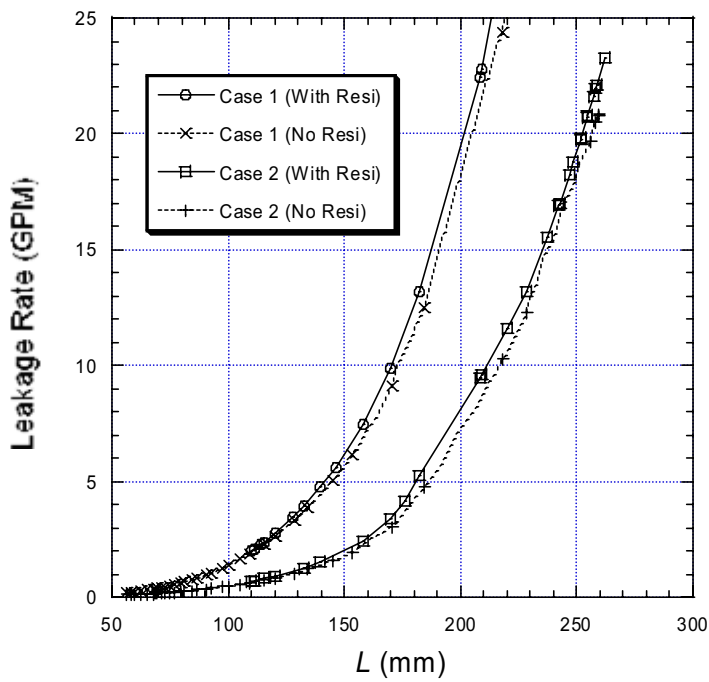Figure 3. Residual stress distribution for weld W2 in Surge line according to [10].

Figure 4. Leakage rate for weld W2 in Surge line as function of crack length with different crack morphology assumptions.
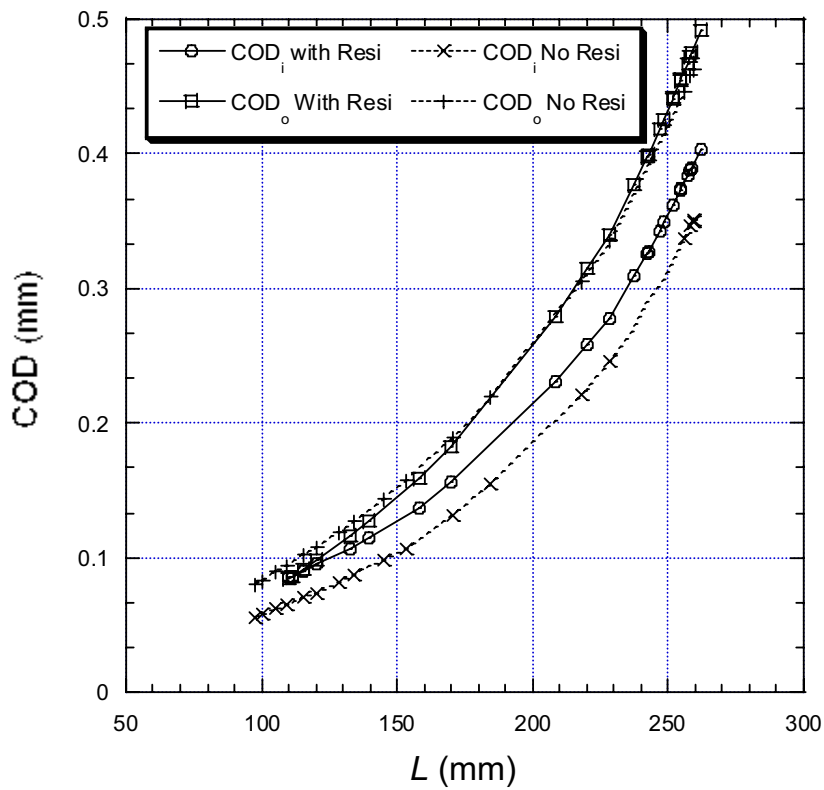
Figure 5. COD for weld W2 in Surge line as function of crack length.

Table 8.1 Average leakage crack size for W2 in surge line.

Residual Stress	Applicant (mm)	Case 1 (mm)	Case 2 (mm)
No	153.2	175.5	218.3
Yes	-	170.0	214.3

Table 8.2 Crack length margins (using critical crack size by ProSACC).

Residual Stress	Applicant critical crack size (mm)	Average critical crack size by ProSACC (mm)	Margin for Case 1	Margin for Case 2	Leakage rate for Case 3 (gpm)
No	423.2	335.5	1.91	1.54	2.85
Yes	-	330.6	1.94	1.54	3.01

8.2 Weld L3W21 in Accumulator Line

As the second example, input data for weld L3W21 in the accumulator line are used. The fluid temperature is increased to 150 °C to make a saturate mixture. The residual stress is here a local bending stress of 215 MPa. The summarized results are listed in Tables 8.3-8.5. As expected, the results with the weld residual stress are more restrictive in the present example. It is noted that if the weld residual stresses are neglected, the required LBB-margins would be fulfilled which is not the case if the weld residual stresses are included for Case 2

Table 8.3 Average leakage crack size at 150 °C for L3W21 in accumulator line.

Residual Stress	Case 1 (mm)	Case 2 (mm)
No	121.7[*]	145.3
Yes	137.1	160.4

* Result for single phase liquid.

Table 8.4 Crack length margins at 150 °C (using critical crack size by ProSACC).

Residual Stress	Applicant critical crack size (mm)	Average critical crack size by ProSACC (mm)	Margin for Case 1	Margin for Case 2	Leakage rate for Case 3 (gpm)
No	346.5	314.9	2.59	2.17	13.04
Yes	-	309.1	2.25	1.93	8.54

Table 8.5 COD by NURBIT and leakage rate by SQUIRT

Residual stress	Case 1			Case 2		
	COD_{in} (mm)	COD_{out} (mm)	Leakage rate (gpm)	COD_{in} (mm)	COD_{out} (mm)	Leakage rate (gpm)
No	0.151	0.193	10.03[*]	0.196	0.251	9.88
Yes	0.276	0.130	10.03	0.335	0.194	10.00

* Result for single phase liquid.

9   DISCUSSION

In this report the influence of crack morphology on Leak Before Break (LBB) margins is studied. The subject of the report is a number of LBB-submittals to SKI where deterministic LBB-margins are reported. These submittals typically uses a surface roughness of 0.0762 mm (300 microinch) and number of turns equal to zero and an in-house code for the leak rate evaluations. The present report has shown that these conditions give the largest LBB-margins both in terms of the quotient between the critical crack length and the leakage crack size and for the leak rate margin.

Crack morphology parameters have a strong influence on the leak rate evaluations. The results in Fig.4 clearly illustrate this conclusion. When a leakage crack length is about 170 mm, for example, the leakage rate is about 10 gpm for Case 1 and only about 3.4 gpm for Case 2.

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. These results are consistent with Wilkowski et al [9].

The effect of including weld residual stresses on the LBB margins is also investigated. It is shown that for the two examples studied, weld residual stresses were important for the small diameter thin wall pipe whereas it was negligible for the large diameter thick wall pipe which had a self-balanced weld residual stress distribution.

10   REFERENCES

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11 TABLE OF REVISIONS

Rev	Page	Changes
1	5	Specify how bending stress is divided into primary and secondary stress part.
1		Tables 5.7, 7.5-7.8, 81.-8.5 have been changed.
2		Program ProSACC is (instead of SACC in the previous revisions) used to calculate the critical crack sizes. The results in Tables 3.6, 3.7, 4.6, 4.7, 5.6, 5.7, 6.6, 6.7, 7.6, 7.7, 8.2 and 8.4 are changed.

APPENDIX 1. A SHORT DESCRIPTION OF NURBIT

NURBIT [1] is an analysis tool which can perform optimization of Risk Informed In-Service Inspection. It can also serve as a database which installs all the information of the welds in piping systems.

NURBIT considers the following damage mechanisms in passive components:
- IGSCC in stainless steel or Inconel piping.
- High cycle vibration fatigue in combination with IGSCC.
- Non-growing defects (manufacturing defects or arresting cracks).

NURBIT uses a probabilistic model based on fracture mechanics where growing cracks can be described by the local stress intensity factor. By including the statistical information about the data that enters this model, the failure probability is evaluated. By combining this with the system barrier probability (or the conditional core damage probability CCDP), a quantitative measure of the core damage frequency CDF, is obtained. The CDF-values are obtained on a component level and represent the risk for core damage per year for this particular initiating event (piping failure). The next step is then to perform a risk ranking of these CDF-values, to select components for inspection and to select the suitable inspection intervals. Different strategies are then possible. NURBIT enables the user to perform different risk-selections. The general objective is to obtain a sufficiently low overall CDF at an optimum amount of inspection costs and radiation exposure to inspection personnel.

NURBIT can also be used to investigate risks and costs when different changes are made in the plant. These changes may include replacement or repair of a component, changed water chemistry or deferred inspection.

In NURBIT, a module to calculate COD for a leakage crack is included. In the present study, this module is utilized to obtain the COD for leakage calculation by SQUIRT [2].

APPENDIX 2. A SHORT DESCRIPTION OF ProSACC

ProSACC is a program developed by Inspecta Technology AB for use by the Swedish nuclear power industry and SKI for assessment of detected cracks or crack like defects, and for defect tolerance analysis.

A fracture assessment procedure based on the R6-method is developed at Nuclear Electric plc. The procedure is described in the handbook [10] which follows with the program. In comparison to the original R6-method this procedure contains a safety evaluation system which for the same set of loads gives similar safety margins against fracture initiation and plastic collapse as applied in the ASME Boiler and Pressure Vessel Code, Sections III and XI.

In the present study, the program is applied to calculate the critical crack size.

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