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CSNI Leak-Before-Break Benchmark – Summary of Phase I

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ABSTRACT

Fourteen organizations, representing eleven countries, participated in a leak-before-break (LBB) benchmark exercise that compared results from analyses among participating countries and identified the effects of weld residual stress (WRS) and crack morphology on crack opening displacement (COD), critical bending moment (CBM), and leak rate (LR) results. The participants determined whether the initial problem would meet their country's LBB acceptance criteria and then evaluated the effects of crack morphology and WRS for a prescribed crack size, geometry and loading.

Six out of fourteen participants indicated that the initial problem met their LBB requirements. In the follow-on tasks, differences among the participants' CBM predictions were principally due to the material properties used in the analysis while the type of failure model chosen contributed much less. Most of the differences in the LR predictions were directly attributable to differences among the COD models, but a portion was attributable to the treatment of crack face pressure (CFP).

The benchmark identified several aspects of an LBB analysis that could support a more realistic evaluation including 1) postulating cracks at the most susceptible location within the weld joint, and utilizing appropriate material properties, crack type, and crack morphology parameters; 2) allowing lower LR detection limits or margins; and 3) more accurately considering both WRS and CFP in LR estimates.

INTRODUCTION

The objectives of this leak-before-break (LBB) benchmark were to compare the results from different LBB analyses among participating countries using common inputs and to evaluate the effects of weld residual stress (WRS) and crack morphology on crack opening displacement (COD), critical bending moment (CBM), and leak rate (LR) calculations in LBB analyses. The benchmark consisted of a baseline problem that was developed so that it would marginally pass the U.S. Nuclear Regulatory Commission (NRC) NUREG-0800 Standard Review Plan (SRP) 3.6.3 acceptance criteria for the piping configuration, assumptions, and inputs considered. Participants were asked to provide a high-level summary of their country's LBB requirements and then evaluate the baseline problem according to these requirements. Four additional tasks that evaluated the effects of different crack morphologies and WRS were defined with the same piping configuration and loading conditions as in the baseline problem but for a prescribed crack length. Fourteen organizations, representing eleven countries, participated in the benchmark.

SUMMARY OF LBB REQUIREMENTS IN PARTICIPANTS' COUNTRIES

The LBB requirements in various countries have been previously summarized by the European Commission (2000), Scott et al. (2002), and Wilkowski (2009). However, several countries have modified their requirements subsequent to the completion of these earlier studies. The OECD/NEA study (OECD/NEA, 2021) provides an in-depth evaluation of the differences in the LBB requirements among the participants' countries; a high-level summary is provided in Table 1.

The requirements in most countries are fundamentally rooted in the U.S. NRC SRP 3.6.3 method, and the basic tenets and underlying principles of the LBB philosophy are generally consistent among all the participants' countries. However, virtually every country has modified either the analysis or acceptance procedure based on additional research and operational knowledge gained since the NRC SRP 3.6.3 method was established. Table 1 next summarizes the three most significant differences between the country-specific requirements and NRC SRP 3.6.3. Some of the more common modifications include explicitly allowing a lower leak rate detection limit (LRDL) than the traditional 0.063 kg/s (1 gpm) limit, requiring an additional subcritical cracking analysis to demonstrate that neither LBB nor inspection intervals are not challenged during operation, and requiring that worst-case strength and toughness properties are chosen from the base and weld metal properties.

The German KTA requirements (KTA, 2014), while philosophically analogous to NRC SRP 3.6.3, differ the most from NRC SRP 3.6.3. No explicit margins on either the LR or the critical crack size (CCS) are required. Rather, the margins are included implicitly in the conservative analysis methods that are used to determine the leakage crack size (LCS) and CCS. The German method is also the only method that requires a flaw growth and stability analysis to first determine the critical surface flaw depth and length and then ensure that an initially presumed surface flaw based on the non-destructive evaluation (NDE) resolution will not grow to this size during the life of the plant.

The Swiss approach is also unique because the principal requirements are that the assessment shall be state-of-the-art and that each LBB application shall propose the method and requirements used to conduct the analysis. A novel aspect in the Swedish requirements (SSM, 2018) is that a specified WRS distribution be applied when determining both the LCS and CCS. Finally, the LBB requirements in Canada (CSNC, 2019) are unique in that they allow probabilistic analysis to supplement the classical deterministic approach. Also, systems with active degradation mechanisms can be approved for LBB if it can be demonstrated that effective aging management is in place to mitigate the degradation.

DEFINITION OF BENCHMARK PROBLEMS

Baseline Problem

The baseline problem required each participant to evaluate LBB according to the methods, requirements, and acceptance criteria that are applicable within their country. A common set of inputs were provided for a surge line pipe with an outer diameter of 406.4 mm and a 40.462 mm wall thickness containing a hypothetical circumferential crack located at the weld centerline (Figure 1). The weld material was specified as nickel-based alloy Inconel A82 while the base material was 304 stainless steel on both sides of the weld. The base and weld material properties are summarized in Table 2. Other inputs included the operating temperature, the normal operation (NO) and safe-shutdown earthquake (SSE) loads, the crack morphology, and the LRDL of 0.061 kg/s (≈ 1 gpm). The NO + SSE loads were assumed to be the bounding transient loads. The input parameters were developed such that the baseline problem just met the acceptance criteria specified in SRP 3.6.3 (2007). More details on the inputs and material properties are provided in OECD/NEA (2021).

Table 1: Summary of LBB Requirements and Significant Differences with NRC SRP 3.6.3

Country	Basic Requirement	NRC SRP 3.6.3 Difference #1	NRC SRP 3.6.3 Difference #2	NRC SRP 3.6.3 Difference #3
Belgium	NRC SRP 3.6.3	Identify loading scenarios other than SSE for stability calcs.	Allow LRDL < 1 GPM (≈ 0.06 kg/s)	
Canada	NRC SRP 3.6.3	Can qualify systems with active degradation if effective aging management justified	Has accepted LR margins less than 10 on a case-by-case basis	May supplement with probabilistic analysis
Czech Rep.	National Req. (1998)	Requires 3 independent LR systems but only 2 needed to quantify LR		
Finland	YVL E.4	Requires fatigue crack growth analysis	Requires weld props. for COD calc., base props. for CCS calc.	Requires that LRDL by qualified by testing and allows LRDL < 1 GPM
Germany	KTA 3206	No explicit LR or CCS margins required; conservatism included in analysis	Requires fatigue crack growth analysis	Requires stability analysis of surface flaw depth and length
Japan	JSME S ND1-2002	Determines second TWC by fatigue analysis of assumed surface flaw	Assesses stability using the larger of the LCS TWC and the fatigue TWC	Required margin of 5 between LRDL and LCS
Korea	KSRG Section 3.6.3	Use of actual material properties preferred		
Sweden	SSM 2018:18	Requires analysis of high & low stress locations	Consider WRS in LR calculations, as applicable	Consider system compliance and applicable crack type
Switzerland	None	No definitive reqs: Both SRP 3.6.3 and break preclusion have been used	Can allow lower LRDL (≈ 0.045 gpm) and increased leak margins	Requires fatigue analysis of assumed surface breaking flaw
United States	NRC SRP 3.6.3	N.A.	N.A.	N.A.

Table 2: Material Properties for Benchmark

Parameter	Strength Properties			Ramberg-Osgood Parameters			J-R Curve Parameters (Δa in mm)		
	E [GPa]	Sy [MPa]	Su [MPa]	σ_0 [MPa]	Alpha [-]	n [-]	Jic [kJ/m^2]	C1	C2
Weld	196.8	316.5	542.4	332.35	0.386	11.39	524.4	586.3	0.661
Base	176.7	153.6	443	200.9	3.75	3.75	1182	355.1	0.728

Task 1 – 4 Problems

A through-wall crack with a 125 mm mid-wall length was specified for Tasks 1- 4. In these tasks, the participants evaluated the effects of crack morphology and WRS on the calculated LR and crack stability using the same geometry, loading and material properties as those for the baseline problem. Table 3 summarizes the unique conditions associated with each of these tasks.

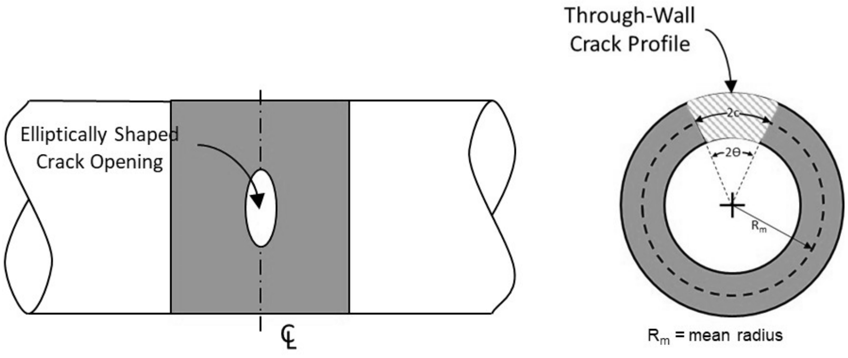

Figure 1: Weld Joint Configuration with Assumed Crack Location and Crack Shape

Table 3: Unique Attributes for Task 1 - 4 Problems

Problem	Mid-wall Crack Length (mm)	Crack Morphology	Applied WRS (Y/N)?
Task 1	125	CF	N
Task 2	125	CF	Y
Task 3	125	PWSCC	N
Task 4	125	PWSCC	Y

Participants were asked to calculate LR and crack stability for two different crack morphologies, corrosion fatigue (CF) and primary water stress corrosion cracking (PWSCC), with and without the following specified WRS distribution, as provided in Brust et al. (2010):

$$\text{WRS (Axial, in MPa)} = -101.3 - 167.58\left(\frac{x}{t}\right) - 375.76\left(\frac{x}{t}\right)^2 + 1165.75\left(\frac{x}{t}\right)^3 \quad (1)$$

The crack morphology parameters were based on the description used in SQUIRT (Rahman et al., 1995) and LEAPOR (Williams and Yin, 2013). This description defines global (μ_G) and local (μ_L) roughness parameters, global (K_G) and local (K_{G+L}) path deviation factors, and factors related to the number of turns per unit length (η_{tL}) for the crack. The SQUIRT/LEAPOR model modifies these values based on COD/ μ_G. Since other LR codes may not have COD-dependent morphology parameters COD-independent morphology parameters were provided (Table 4). This COD dependency was eliminated by equating the global and local parameter values and choosing effective η_{tL} values that approximately represent the SQUIRT/LEAPOR η_{tL} values based on the estimated COD for the Task 1 – 4 problems. While physically unrealistic, these parameters produce results that closely approximate those using the COD-dependent parameters codified in SQUIRT/LEAPOR for these problems.

Table 4: Benchmark Crack Morphology Parameters

Parameter		
	CF	PWSCC
μ_G	40 µm	114 µm
μ_L	40 µm	114 µm
K_G	1.1	1.2
K_{G+L}	1.1	1.2
$\eta_{t(90)}$	1730 m^{-1}	5020 m^{-1}

RESULTS

Baseline Problem

The LCS for the country-specific analyses is plotted for each crack-morphology-type chosen in Figure 2. In this figure, AF represents an air fatigue crack-type morphology, while the CF and PWSCC crack-types were previously defined. The large scatter apparent in this figure results from several factors. Crack morphology is one important factor as the highest LCS values were calculated when the most tortuous PWSCC-type morphology was assumed. Conversely, the participants that obtained the two lowest LCS values assumed very flat AF morphologies. Another important factor is the LR used to calculate the LCS. The two lowest CF LCS results used LR values that were at least 50% less than the 0.61 kg/s (≈ 10 gpm) value used by most other participants. Using the lower-strength base material properties for calculating COD and not accounting for CFP effects (not shown) also decreased the reported LCS values. Finally, while the higher LCS values were obtained by the participants using the SQUIRT/LEAPOR codes (Figure 2), it is expected that the modelling choices just discussed were the causal factors and not the result of any significant LR code biases.

The LCS and CCS results are illustrated in Figure 3. The LCS (orange bars) and CCS (grey bars) values are paired for each participating organization. The label above the LCS bars depict the material strength properties that were used in the COD determination (i.e., "B"ase, "W"eld, or "M"ixture properties). The labels above CCS bars indicate whether an elastic-plastic fracture mechanics (EPFM), net-section collapse (NSC), or failure assessment diagram (FAD) approach was used to calculate the CCS, and the material strength properties that were used in the calculation.

The average CCS/LCS ratio among participants that calculated both values is 1.8. Since most countries require that CCS/LCS > 2 to meet LBB requirements, this average is consistent with the finding that only six out of fourteen participants indicated that the baseline problem met their LBB requirements. The likelihood that LBB can be demonstrated decreases as LCS increases and/or CCS decreases. Reasons for variations in the LCS have been previously discussed (Figure 2). Figure 3 illustrates factors that affect the CCS calculation. The biggest reason for variability among the CCS values was the material strength properties used in the analysis. The average EPFM values calculated using weld metal properties are ≈ 45% greater than the average values calculated using base metal properties. Similarly, the average CCS NSC values calculated using weld metal properties are ≈ 50% greater than the average NSC and FAD values calculated using base metal properties.

It is also apparent that the EPFM approach typically results in a slightly larger CCS than either the NSC or FAD methods for the baseline problem. The average EPFM-calculated CCS values using weld properties are ≈ 15% greater than the average NSC-calculated values using weld properties. Organizations performing both EPFM and NSC methods also indicated that the NSC CCS values were smaller, or more conservative, and were therefore the results that they reported. While these differences are not as great as those resulting from the choice of material properties, they can make a difference in determining whether a marginal LBB configuration, such as the baseline problem, passes the LBB requirements.

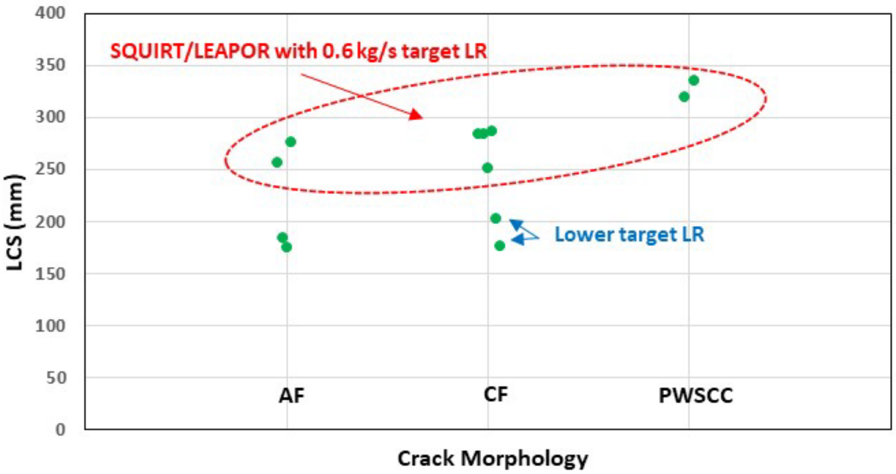

Figure 2: Influence of Crack Morphology on LCS

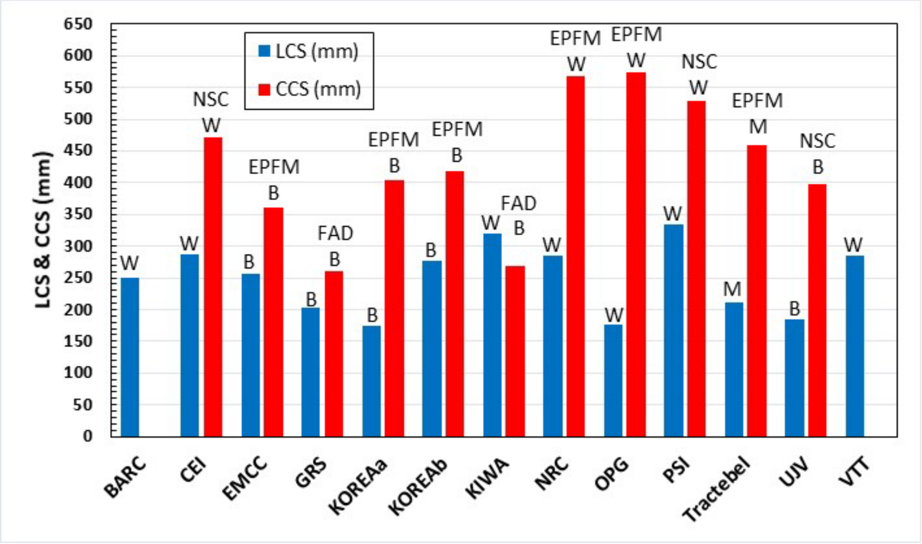

Figure 3: Summary of LCS and CCS Results

Task 1 – 4 Problems

The critical bending moment (CBM) for crack instability of the 125 mm long crack prescribed in these tasks is summarized in Figure 4. In this figure, participants have been grouped by the failure model (i.e., EPFM, NSC, or FAD) and strength properties used within their analysis. Since a single crack length was specified, the effects of failure model and material properties are emphasized. As seen previously, the material properties used in the analysis accounts for most of the CBM variability, with the average CBM for all participants using EFPM with B strength properties being approximately 44% less than the average CBM for those participants using EPFM with W properties. As in Figure 3, Figure 4 also shows that another reason for the high variability in the CBM results is the failure model type used in the analysis. The average CBM for those participants using NSC with W properties is 7% less than the average CBM for participants using EPFM with W properties. Further, if results are grouped by the failure model and material property choices (i.e., EPFM/W, EPFM/M, EPFM/B, NSC/W, FAD) and analyzed separately, the variability among the participants' predictions is substantially reduced.

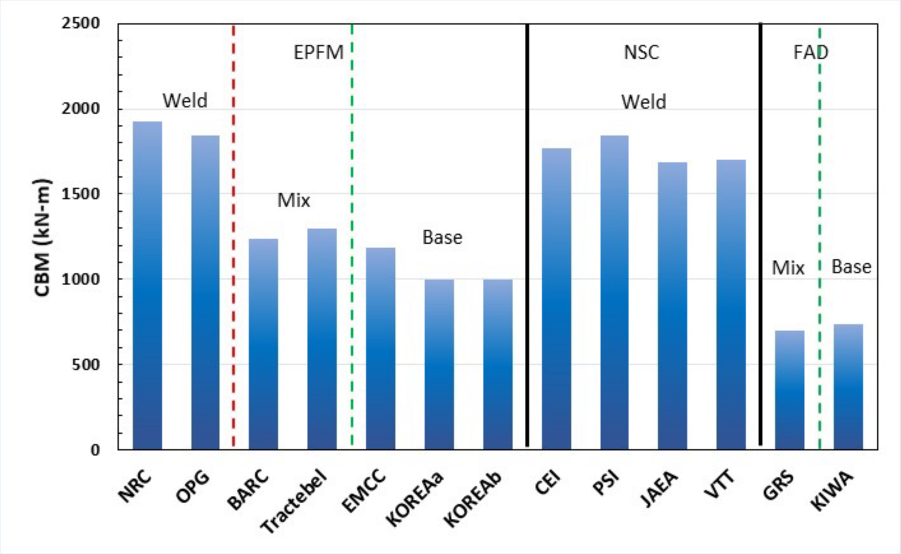

Figure 4: CBM Results for Task 1 (i.e., CF crack morphology without WRS)

Inclusion of CFP (not shown) slightly decreases the predicted CBM but is a much less important consideration than the failure model choice and strength properties. Similarly, the incorporation of WRS in Task 2 did not significantly affect the CBM results except for 2 participants who used the R6 method of Milne et al. (1988) as this method explicitly considers WRS as an as additional contribution to the stress intensity factor. Using this approach, the Task 2 CBM values for these two participants were approximately 23% lower than their Task 1 CBM predictions.

The LR predictions are strongly impacted by the crack morphology and WRS parameters. The Task 1 (CF morphology without WRS) and Task 3 (PWSCC morphology without WRS) LR results are illustrated as a function of the mid-wall COD (MWCOD) in Figure 5. For the fixed crack size and linear loading distributions in these tasks, the MWCOD and LR results are fairly well correlated. The CF morphology results (filled circles) are well-represented by the black dashed linear trend line over the range of reported MWCOD values. The PWSCC morphology results (filled squares) are also approximately linear except for the two participants that reported zero LR because of crack closure at the ICOD (see Figure 7).

There is also a clear effect of crack-face pressures (CFP) on the results. The lowest reported MWCOD results (i.e., those to the left of the red-dashed line) did not consider CFP effects while those results to the right of this line did. This explains some, but not all, of the MWCOD variability apparent in the participants' results. The variability is more fully explained by considering that the differences in the MWCOD values for the CF morphology results contribute approximately 80% of the differences in the LR predictions (r^2 value of 0.81). This highlights the importance of the MWCOD predictions and implies that more accurate and consistent COD predictions would greatly reduce differences in the LR predictions.

The more tortuous PWSCC morphology led to smaller LR predictions for all participants, with the mean PWSCC LR being 22% less than the mean CF LR. The Task 1 PWSCC morphology LR predictions have a standard deviation is about 44% of the mean compared to only 27% for the CF morphology LR predictions. However, the standard deviation among the PWSCC results among those considering CFP is only 18%. Therefore, much of the variability in the LR predictions for the PWSCC morphology is also directly correlated with the choice of incorporating CFP.

Because all but three of the participants used a variant of the SQUIRT or LEAPOR codes, these results are identified separately in Figure 5. While the SQUIRT/LEAPOR codes appear to be slightly less conservative (i.e., higher LR for a given COD) than the other codes for the prescribed CF morphology, there is not enough data to determine if this trend is statistically significant. Further, the average LR and standard deviation do not change significantly when calculated for all results or only the SQUIRT/LEAPOR results. This result provides additional evidence that apparent LR code differences in this benchmark may largely be a function of the differences among MWCOD results rather than use of a particular leak rate code.

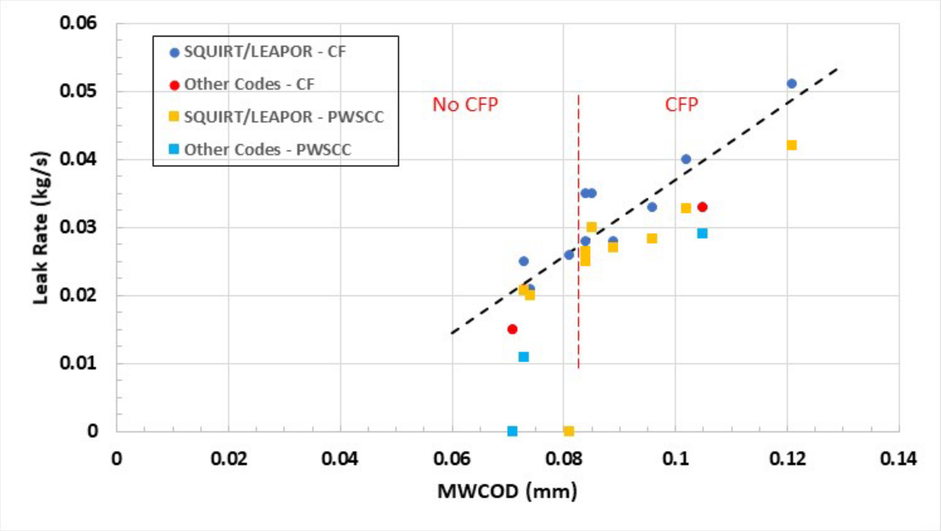

Figure 5: Mid-wall COD vs LR without WRS Effects

The effect of WRS on the MWCOD and LR is illustrated as ratios of the Task 2 results (i.e., those with WRS) to the Task 1 results (i.e., those without WRS) in Figure 6. As seen, the MWCOD ratio values predicted by the participants were reasonably consistent between Tasks 1 and 2 (i.e., COD ratio values near 1), the implication being that the prescribed WRS did not significantly affect the MWCOD values. However, more significant effects were apparent in those participants' results that independently calculated inner-diameter COD (ICOD) and outer-diameter COD (OCOD) values.

The reported through-thickness COD values when incorporating the prescribed WRS distribution in Task 2 is shown in Figure 7. The ICOD, MWCOD, and OCOD values are connected by smooth lines as a visual aid only, as each participant only reported the three discrete COD values. These profiles are much more variable than the linear COD profiles reported without WRS in Task 1 (not shown). Linearity is only evident in the few results that analytically incorporated WRS effects in Task 2, while the remaining COD profiles for participants that incorporated WRS effects through finite-element modelling are all non-linear. Further, four participants predicted negative or zero ICOD values for this task.

While consideration of WRS had little effect on MWCOD Task 2 / Task 1 ratios, it more significantly affected the LR results compared to those predicted in Task 1 (Figure 6) because of significant changes in IDCOD and ODCOD (Figure 7). While four participants predicted Task 2 LR values within 20% of their Task 1 values --- which was consistent with differences in MWCOD values --- the remaining participants predicted more significant differences, including those that predicted no LR due to zero or negative ICOD values. Most participants predicted smaller LRs due to the WRS effects. However, two of the participants predict higher LRs due to the prescribed WRS distribution when using the MWCOD as the input to their LR codes. This likely occurs because they predicted that the WRS increases the MWCOD (Figure 6).

The increased variability in the LR predictions is driven by increased differences among the participants' predicted COD profile induced by WRS, the input COD parameters chosen by the participants for LR calculation, the inclusion of CFP, and possible differences in how the LR codes manipulate the input COD parameters (e.g., by averaging them to obtain a single measure) to ultimately determine the predicted

LR. Similar WRS effects were apparent for the PWSCC morphology. In fact, the percentage decreases in the LR results between Tasks 1 and 3 (i.e., without WRS effects) and Tasks 2 and 4 (i.e., with WRS effects) were reasonably consistent among participants, which implies that the WRS effects affected the LR for both morphologies to roughly the same degree.

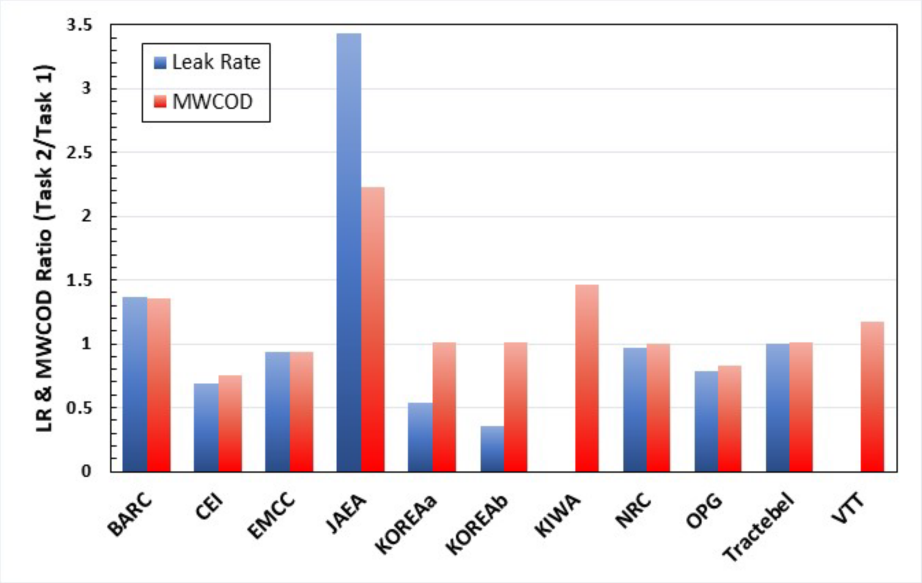

Figure 6: Effect of WRS on MWCOD and LR for CF Morphology

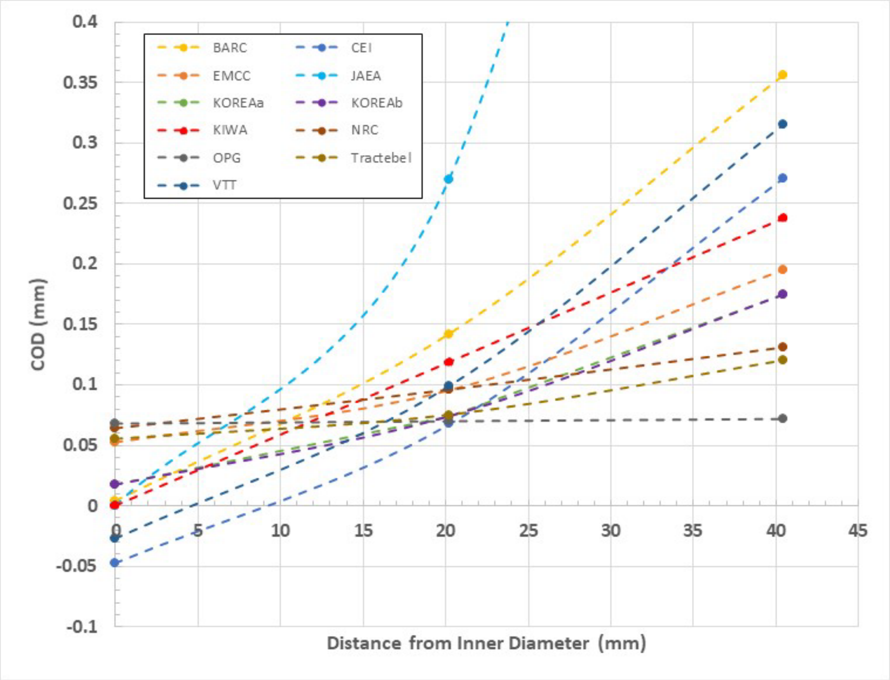

Figure 7: Through-Thickness COD Profile with WRS (i.e., Task 2)

SUMMARY

The high-level summary of the LBB requirements in each of the participating countries revealed that the basic tenets and underlying principles of the LBB philosophy are generally consistent among countries. Most countries' procedures are rooted in NRC SRP 3.6.3 but virtually every country has modified either the analysis or acceptance procedure based on additional knowledge gained since NRC SRP 3.6.3 was established. Some of the more common modifications include explicitly allowing a lower LRDL, allowing a lower LRDL margin, requiring an additional subcritical cracking analysis to demonstrate that LBB or inspection intervals are not challenged, and requiring that worst-case strength and toughness properties are chosen from the base and weld metal properties. These modifications represent a natural progression of both technical and operational knowledge since NRC SRP 3.6.3 was first established.

The baseline problem achieved its initial objective of being "marginal" as eight participants indicated that it is not acceptable for LBB while six participants indicated that it is acceptable for LBB. The principal factors in determining whether the baseline problem was met the respective countries' LBB acceptance requirements were the choice of the material properties to determine the CCS, the assumed crack type and its associated morphology, and the LRDL used to determine the LCS. A secondary consideration was the type of failure model (i.e., NSC, FAD, of EPFM) used in the crack stability analysis.

The effects of crack morphology and WRS were systematically evaluated in Tasks 1 – 4, and the participants were asked to provide the COD, CBM, and the associated LR for the prescribed crack, geometry and loading. Similar to the baseline problem, differences among the participants' CBM predictions were principally due to the material property choice (i.e., weld, base, mixture), while the type of failure model (i.e., NSC, FAD, or EPFM) contributed much less to the differences. Most of the differences in the LR predictions were directly attributable to differences in the COD models, but a portion was attributable to the inclusion of CFP. The small differences in LR predictions that may be directly attributed to the LR codes may imply that differences in how these specific codes model the relationship between LR and COD may not be significant, at least for the fixed crack morphology and length evaluated here.

Changing the crack morphology from CF to PWSCC decreased the predicted LRs for the specified crack size. There was much more variability in the LR predictions for the PWSCC morphology than for the CF morphology, but much of the additional variability could be directly correlated with the choice to incorporate CFP. Those participants that did not consider CFP typically predicted a greater reduction in LR due to the PWSCC crack morphology.

Incorporating the prescribed WRS distribution also had an impact on the predicted COD and LR results. Several participants predicted that WRS resulted in a relatively modest 20% change in LR for the CF morphology, while participants that used finite element modelling to apply the WRS distribution predicted more significant effects on the LR predictions. In general, the smallest LRs were predicted for the PWSCC morphology when the WRS was applied, but the percentage decrease in the LR due to the applied WRS was consistent for the CF and PWSCC morphologies among many of the participants' results.

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