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# INTERNATIONAL LEAK RATE BENCHMARK: PHASE ONE RESULTS OF THE OECD/NEA/CSNI ACTIVITY

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## ABSTRACT

The metals sub-group of the Working Group on Integrity and Ageing of Components and Structures (WGIAGE) of the Committee on the Safety of Nuclear Installations (CSNI) of the Nuclear Energy Agency (OECD/NEA) launched a benchmark activity on the comparison of leakage rate computation practice and the applied tools and software solutions, allowing the identification of best practices. Participants from 11 organizations and 9 countries contributed to this round robin activity. The paper summarizes the results of the first phase of the benchmark, consisting of a laboratory test of an artificial slit, a laboratory test of a fatigue crack, a real leak event, and a sensitivity study related to leak-before-break assessment. In general, the comparison shows a good agreement between the computations and the measured leak rates in the laboratory tests. Differences between participants can be explained with model choices and input data sets.

## INTRODUCTION

The mass flow rate through a wall-penetrating defect in a pipe or component of a nuclear power plant is an important quantity for the safety assessment, as it is related to the opportunity of rapid detection and mitigations, but also with respect to loss of reactor core coolant. Therefore, computational models for the prediction of the mass flow rate through defects have been developed, and several experimental tests were performed to validate the models.

In 2019, the Working Group of Integrity and Ageing on Components and Structures (WGIAGE) of the Committee on the Safety of Nuclear Installations (CSNI) of the Nuclear Energy Agency (OECD/NEA) discussed and finally launched the benchmark on leak rate computation. One important foundation for this activity is leak rate testing performed at the Materials Testing Institute (MPA) University of Stuttgart, see Schmid et al., 2021. The present paper describes the test cases and results of the first phase of the activity, where the problem sets are designed as non-blind cases (what means that measured leak rates are passed to the participants together with the case descriptions).

This paper is organized as follows. In the section on method and tools, the constituents of a leak rate computation are discussed, and the applied tools within the benchmark are briefly described. In the section about test cases, the four main cases are discussed in individual sub-sections. The paper ends with a summary and conclusion.

## METHODS AND TOOLS

In the prediction of the mass flow rate through a crack-like leak in a pipe or component, usually the geometry of the pipe and the flaw, the material and the applied loads are known, as well as well as the morphology of the crack surfaces and the fluid conditions. With this information, the three building blocks of leak rate evaluation can be determined: the leak opening, the flow resistance and the leak rate. With the opening model, the leak opening is computed under the consideration of pipe and crack geometry, material property and loading. The friction and resistance model computes a flow resistance based on morphology parameters and the leak opening. The flow model, finally, computes the leak rate itself based on the leak opening, the flow resistance and the fluid. This dependence is visualised in Figure 1.

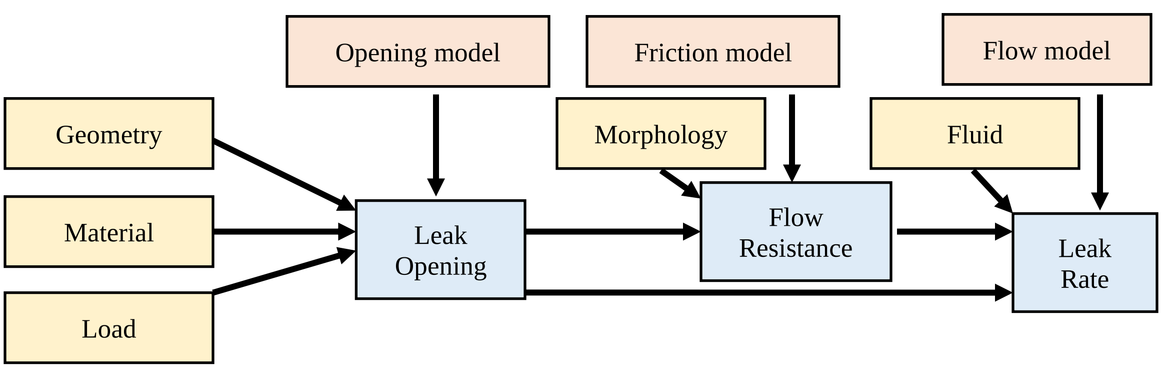


Figure 1. Input data (yellow) and models for determination of further input data (red) in the intermediate steps (blue) of a leak rate assessment.

In each leak rate computation, models for these key constituents must be selected, but it is in principle possible to combine the models arbitrarily. Therefore, it is essential to understand the ingredients of a leak rate computation, and the comparison of intermediate results of leak opening and flow resistance help to understand differences in computational approaches and final results. The diagram in Figure 1 also underlines the role of the leak opening computation: As the starting point in the calculation, the computed opening influences the following stages of the computation chain. In addition, it shows that the friction model is a conscious choice of model and input data in the form of anticipated morphological parameters, and its importance is expected to be higher than the choice of the flow model (see Heckmann et al., 2018).

Among the participants, several different software tools with implementations of the models are used which have relations between each other. The SQUIRT code (Paul et al., 1994) developed at Battelle has the derivative code ExcelSQUIRT, which uses spreadsheets as input data format. The LEAPOR code (Oak Ridge, see Williams et al., 2017) implements basically the same thermohydraulic models as SQUIRT, with updated quality assurance standards. The OCI-developed LOCI™-code is an extension of LEAPOR with more modular leak rate models. The PICEP code (EPRI, Norris and Chexal, 1987) was later extended to the SI-PICEP code also for quality assurance standard compliance. The codes WinLeck (GRS, see Bläsius et al., 2019), SCALE (BARC) and LEAKH (UJV) are also used within the benchmark activities.

## TEST CASES

In this section, the cases are presented together with the contributed analyses. In each of the four cases, the identified reasons for differences between the participants are highlighted. It should be noted that the case description for the participants were provided in the form of a table, whereas for the format of this paper, the information is given as a text.

### *Artificial Slit*

The artificial slit case is based on measurements at the FSI test rig at the MPA University of Stuttgart. The benchmark participants received a tabular description of the leak specimen under investigation: An approximately rectangular slit machined in a plate of 30 mm thickness. On the inside surface the slit is 27 mm long and has a width of 192 µm and 201 µm at the ends and 190 µm in the centre. On the outside surface the end widths measure 185 µm and 239 µm, and 229 µm at the centre. The inside and outside cross sections have estimated values of 5.22 mm² and 6.22 mm², respectively. The surface roughness is 22 µm, and a (unitless) total flow resistance of 4.32 was measured in cold-water tests. Six measured leak rates at different temperature and pressure conditions are to be analysed.

The six fluid conditions in the pressure-temperature diagram of water are shown in Figure 2. In the comparison, it turned out that most of the differences between the computational results can be explained with the flow resistance assumption; therefore, a grouping according to the resistance model is shown in the same figure.

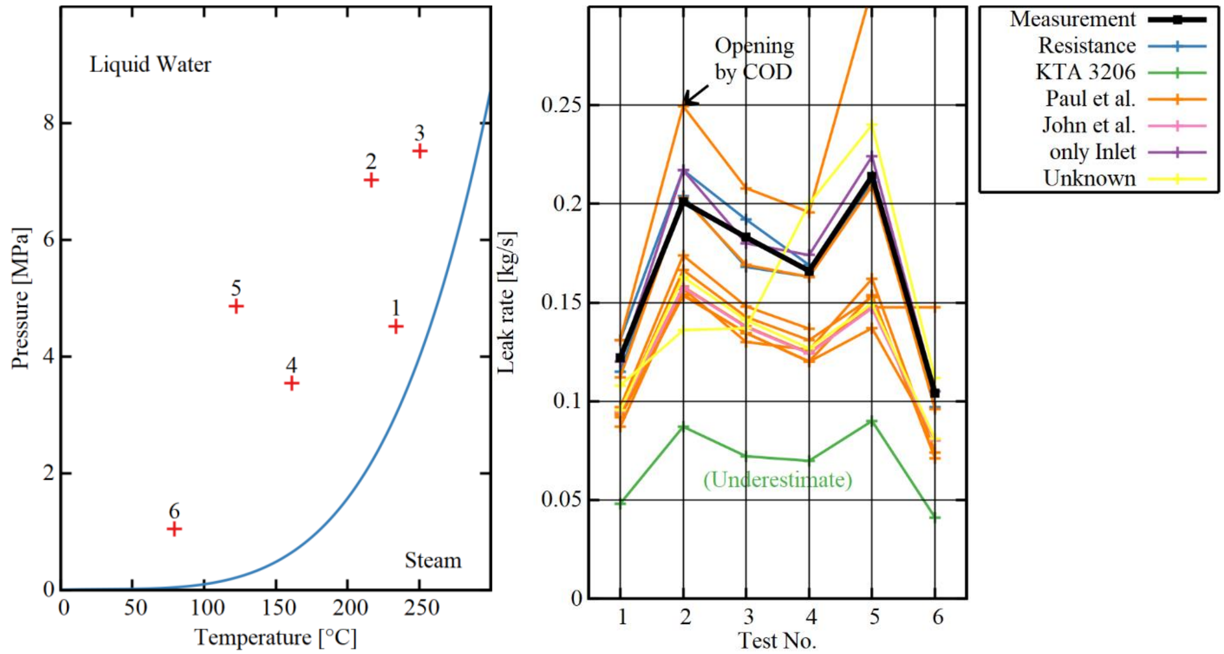


Figure 2. Artificial slit cases and analysis of friction assumptions

Two of the contributions are outliers: One intentionally underestimating analysis, which is based on the KTA 3206 resistance model, and one which is based on the crack opening displacement (COD), a value that is not accurate enough due to the irregular shape of the slit. Many other participants use the resistance by Paul et al. (1994) which results in this case of a slight underestimation of the measured leak rates. The use of the cold-water resistance leads to a much higher accuracy as it uses additional information from the experiment.

### *Fatigue Crack*

The fatigue crack case is based on another experiment at the FSI test rig at MPA University of Stuttgart. A fatigue crack was created in an austenitic steel plate witha section having 7.8 mm thickness. At the interior side, the crack has a full length of 53.89 mm and a maximal width of 79 µm (cross section of 4.26 mm²), while at the exterior side, the crack length is 39.04 mm, the width is 48 µm and the cross section is 1.87 mm. The surface roughness is 40 µm, and the measured flow resistance during the test is 40. Six selected measurements at different temperatures and pressures were provided and constitute the analysis cases.

The six fluid conditions are depicted in Figure 3 in the $pT$-diagram of water. As the main influence in this test was found to be the flow model, the contributions are grouped by this property in the figure. It should be noted that LEAPOR refers to the implementation of the Henry-model in the LEAPOR-code, Mod. B. is the modified Bernoulli equation, and HE the homogeneous equilibrium model.

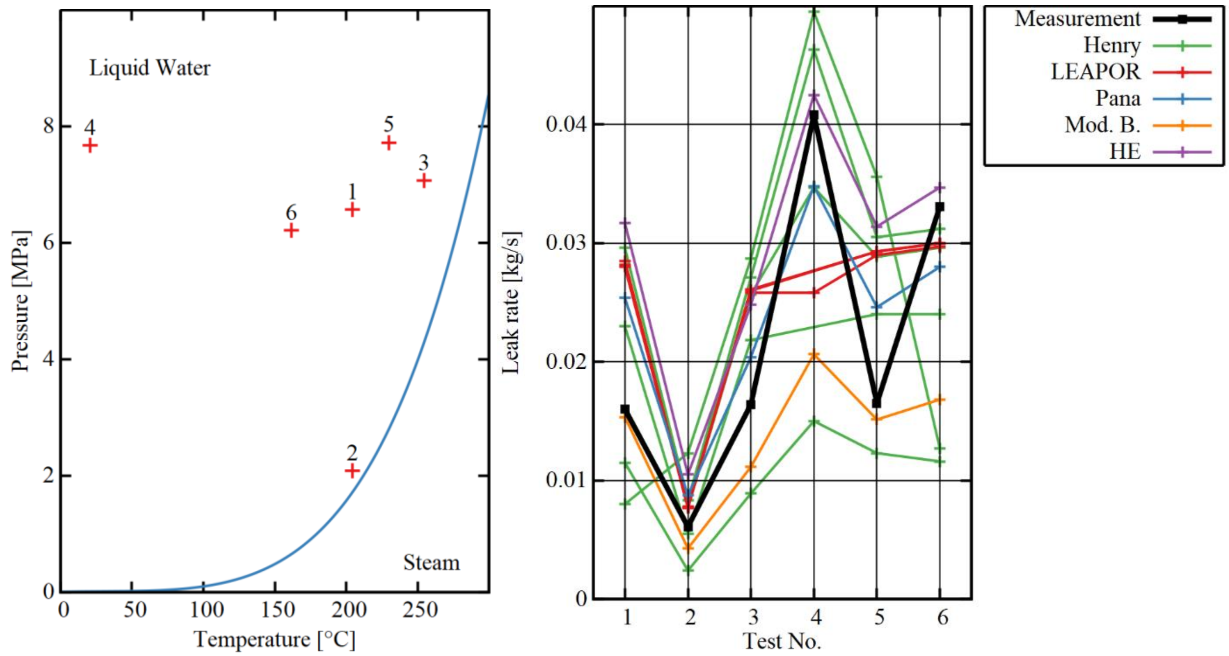


Figure 3. Fatigue crack cases and analysis of flow model assumptions

The grouping of the results can be understood well with the flow model analysis. The LEAPOR-implementation (Williams et al., 2017) of the Henry-model (Henry, 1970) has a different exception handling in case of cold-water flow (Test No. 4), where the strict Henry model is not meaningful. The similar observation can be made for the modified Bernoulli model (Zaloudek, 1963). Although different choices of the flow resistance models were made, as discussed for the Artificial Slit case, the impact on the result is not so significant. A reason for this might be that the friction influence is much higher in the fatigue crack case than for the artificial slit case.

***Real Event***

As an example of a leak from a real event in an operating plant, the case described by Herbst et al. (2001) is chosen. A pipe with an outer diameter of 37.7 mm and 4.33 mm thickness is made of the austenitic material 1.4550. Young's modulus is 186 GPa, the yield stress ($R_{p0,2}$) is 167 MPa and the ultimate stress is 409 MPa. The Ramberg-Osgood coefficients of the stress strain relation are $\alpha = 15.5$ and $n = 2.5$. The pipe is operated at an interior pressure of 15.9 MPa and in a temperature range of 40-70 °C. A circumferential crack with a length of 40 mm, 36 mm and 34 mm (interior surface, mean, exterior surface, respectively) is in the pipe; the maximal width of the crack is only roughly estimated. The average crack roughness is 7.6 µm, the mean roughness is 2.3 µm, and the maximal roughness is 10.6 µm. A leak rate of 13 g/s is reported.

The unknown quantity in this analysis is the bending moment acting on the pipe, which causes a significant contribution on the crack opening displacement. Therefore, the participants are asked to give an estimate of a realistic bending moment and a maximal bending moment in the computation, together with a leak rate assessment at zero bending moment. Moreover, in addition to the best-estimate assessments, over-estimate and under-estimate contributions were requested. The comparison of the computed leak rate as a function of the bending moment is shown in Figure 4. In addition, the leak rate is also shown as a function of the crack opening area COA.

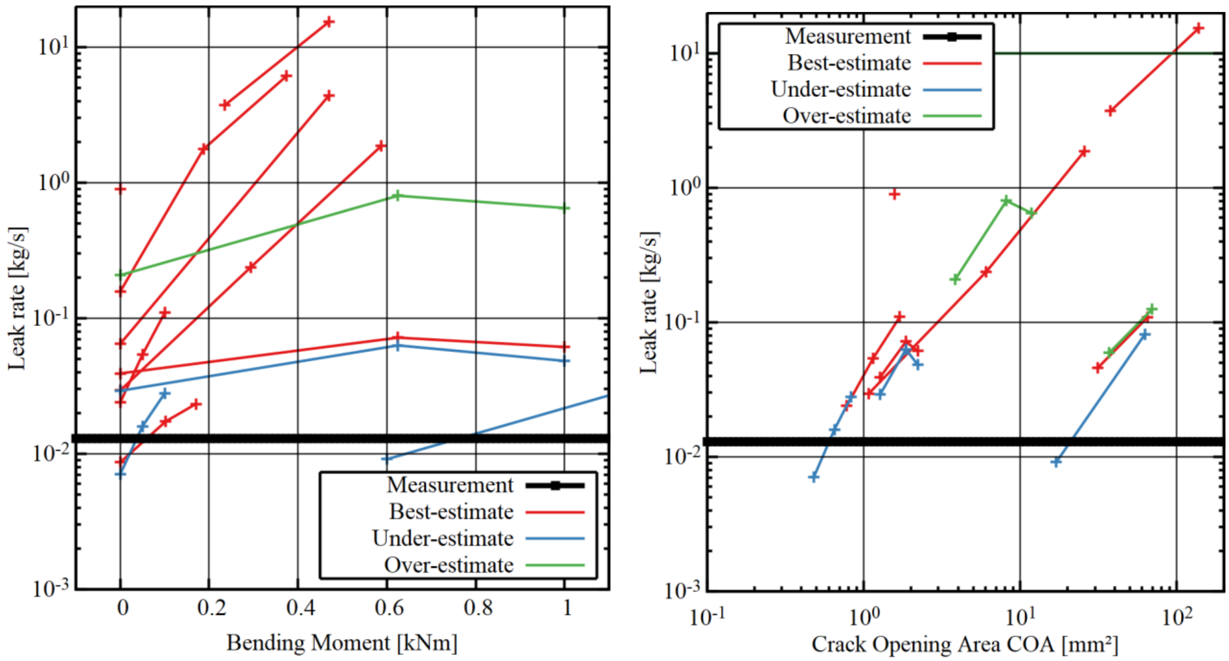


Figure 4. Bending moment of real event case and Influence of opening area computation

The estimated maximal bending moments range from about 0.1 kNm to about 1 kNm, with many received values in the range of 0.4 kNm. One singular contribution assumes much higher bending moments. The under-estimate contributions are in most cases lower than the best-estimate contributions. From the depiction of the dependence of leak rate on opening area, it becomes apparent that the leak rate prediction as a function of COA is very consistent between the participants (except for one outlier). This indicates that the main reason for differences among participants is in the computation of the crack opening, or equivalently in the COD computation.

### *Leak-before-break Sensitivity Study*

The leak-before-break case investigates a specific issue identified in the parallel leak-before-break benchmark activity, see Tregoning et al. (2022). A weldment of a 406.4 mm outer diameter pipe with wall thickness of 40.362 mm (weld width 50.8 mm) is investigated. The material properties are reported in Table 1. The pipe is exposed to an axial force of 17.34 kN as primary load and -4 kN as secondary load. A crack face pressure of 7.75 MPa is assumed. The primary bending is 21.59 kNm and the secondary bending is 68 kNm.

Table 1. Material parameters of the leak-before-break case

| | Yield strength Rp02 [MPa] | Ultimate strength Rm [MPa] | Elastic modulus $E$ [GPa] | Poisson number $\nu$ | Ramberg-Osgood Parameters | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | $\sigma_0$ [MPa] | $\varepsilon_0$ | $\alpha$ | $n$ |
| Base | 153.6 | 443 | 176.7 | 0.3 | 200.9 | 1.1eE-3 | 15.64 | 3.75 |
| Weld | 316.5 | 542.4 | 196.8 | 0.3 | 332.35 | 1.69E-3 | 0.386 | 11.39 |

The damage mechanism of primary water stress corrosion cracking is assumed, with a local surface roughness of 17 µm, a global roughness of 114 µm, bends in the flow path of 5020 1/m in case of COD-independent turn density and 5940 1/m in case of COD-dependent turn density, and a path deviation of 1.2 was assumed. The pipe is operated at a pressure of 15.5 MPa and a temperature of 340 °C. For the analysis, a crack length between 50 mm and 300 mm was assumed, and the leak rate was computed. As a variant, a local surface roughness of 17 µm was assumed. Instead of discussing the leak rate as a function of the full crack length, different intermediate results are presented in Figure 5.

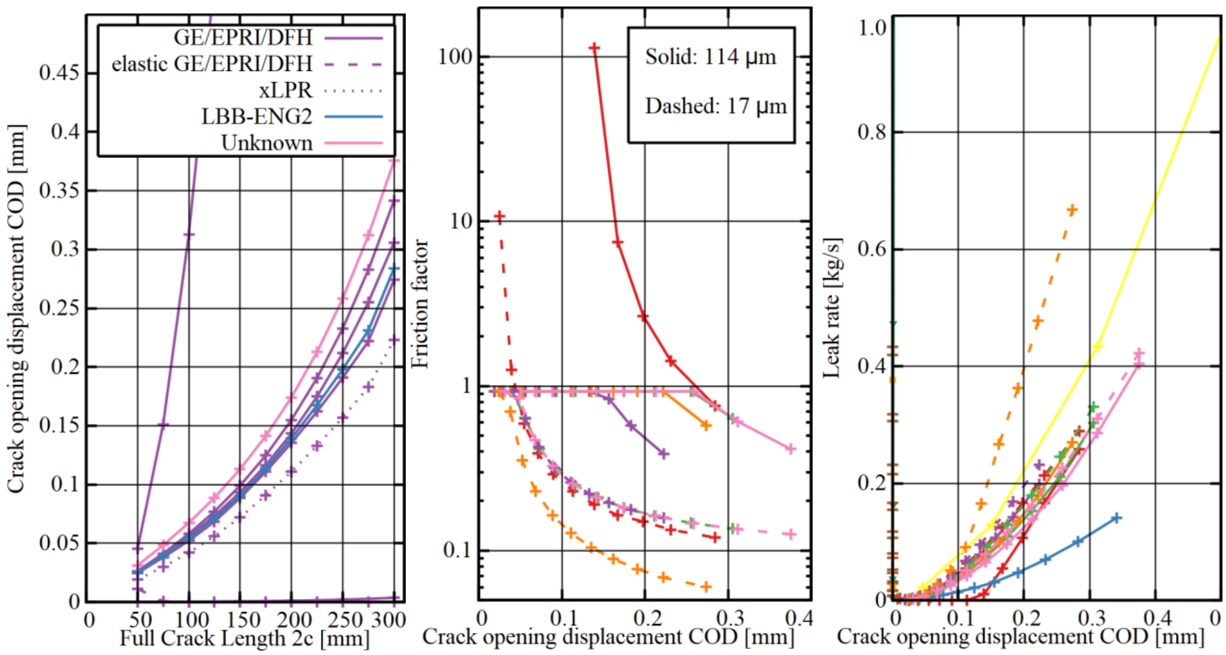


Figure 5. LBB sensitivity study with intermediate results

The computed COD as a function of the full crack length is shown in the left diagram of Figure 5, grouped by the applied computation method. Most participants rely on the GE/EPRI method (Kumar et al., 1981 and 1984). The computed crack opening already shows a scattering between the contributors and also shows two outliers. The centre figure shows the computed friction factor as a function of the COD for 114 µm and 17 µm. It is noted that not all participants were able to report this parameter. This shows that the morphological difference results in a grouping of the contributions by the different friction factors, i.e., the higher local roughness leads consequently to higher friction factors. It is also apparent that some participants truncate the friction relation to values of about 1, while others don't. These factors provide an understanding of the right figure, where the leak rate is shown as a function of COD in identical color codes. Also, these same factors help to understand the solid-red line, which predicts rapidly decreasing leak rates for COD in the order of the local roughness, as well as the dashed-orange line, which has the lowest friction factors and consequently the highest leak rates.

## SUMMARY AND CONCLUSIONS

This benchmarking activity investigated four major cases for the leak rate assessment: A laboratory test of an artificial slit, a laboratory test of a fatigue crack, a real event, and a sensitivity study related to leak-before-break assessment. Participants from 11 organizations and 9 different countries contributed analysis results, which were compared with a special emphasis on the underlying models.

The contributions showed that the leak rate models are capable of predicting leak rate tests in laboratory conditions with a satisfying accuracy. The analysis case of the real event showed that the accuracy is limited due to missing information, but the selected case can be seen as a credibility check which most of the contributors were able to satisfy. The leak-before-break sensitivity case indicated that the morphological parameters and flow resistance models can have a significant impact on leak rate computation. In total, the concept of analysing and comparing intermediate results of the computation was shown to be very effective.

While the presented benchmark phase consists of non-blind analysis cases, the second phase of the activity deals with blind analysis cases. The results of this second phase will be covered in a later publication.

## REFERENCES

Bläsius, C., Heckmann, K., Sievers, J. (2019). „Quality Management, Verification, and Validation of Structure Mechanical Computer Codes at GRS," *Structural Mechanics in Reactor Technology (SMiRT-25),* Charlotte, NC, USA

Heckmann, K., Sievers, J. and Weyermann, F. (2018). "Leak Rate Computation: Flow Resistance vs. Thermal-Hydraulic Aspect," *ASME Pressure Vessel and Piping Conference*, PVP2018-84534, Prague, Czech Republic

Henry, Robert E. (1970). "The Two-Phase Critical Discharge of Initially Saturated or Subcooled Liquid," *Nuclear Science and Engineering*, 41 (3) 336-342 DOI:10.13182/NSE70-A19091

Herbst, O., Huber, N. and Kastner, W. (2001). "Application of the Leak Flow Rate Calculation Program FLORA to Real Cracks in Piping," *Structural Mechanics in Reactor Technology* (*SMiRT-16)*, Paper #1919, Washington DC, USA.

John, H., Reimann, J., Westphal, F. and Friedel, L. (1988). "Critical two-phase flow through rough slits," *International Journal of Multiphase Flow*, 14 (2) 155-174, DOI:10.1016/0301-9322(88)90003-1 .

KTA Nuclear Safety Standards Commission (2016). *Break Preclusion Verifications for Pressure-Retaining Components in Nuclear Power Plants*. KTA 3206, Bundesamt fuer kerntechnische Entsorgungssicherheit (BfE), Salzgitter, Germany.

Kumar, V., German, M.D. and Shih, C.F. (1981). *An Engineering Approach for Elastic-Plastic Fracture Analysis*, EPRI-NP-1931, Electric Power Research Institute, Palo Alto, California, USA.

Kumar, V., German, M.D., Wilkening, W.W., Andrews, W.R., deLorenzi, H.G. and Mowbray, D.F. (1984). *Advances in Elastic-Plastic Fracture Analysis*, EPRI-NP3607, Electric Power Research Institute, Palo Alto, California, USA.

Norris, D M, and Chexal, B. (1987). *PICEP: Pipe Crack Evaluation Program (Revision 1),* Electric Power Research Institute (EPRI), Report EPRI-NP-3596-SR-Rev.1, Palo Alto, California, USA

Paul, D.D., Ahmad, J., Scott, P.M., Flanigan, L.F. and Wilkowski, G.M. (1994). *Evaluation and refinement of leak-rate estimation models. Revision 1,* NUREG/CR-5128-Rev.1, BMI-2164-Rev.1, Columbus, Ohio, USA.

Pana, P. and Müller, M. (1978). "Subcooled and two phase critical flow states and comparison with data," *Nuclear Engineering and Design*, 45 (1) 117-125 DOI:10.1016/0029-5493(78)90110-3

Schmid, S., Silber, F.E., Heckmann, K., Kulenovic, R., Laurien, E., Sievers, J. and Weihe, S. (2021). "Leak rate testing in the range of leak detection systems," *Nuclear Engineering and Design,* 372, 111000 DOI:10.1016/j.nucengdes.2020.111000 .

Tregoning, R., Wallace, J., Bouydo, A., Costa-Garrido, O., Dillström, P., Duan, X., Heckmann, K., Kang, S.Y., Kim, Y.-B., Kim, Y., Kuutti, J., Mano, A., Niffenegger, M., Samohyl, P., Singh, P.K., Kurth Twombly, E. and Yang, S. (2022). "CSNI Leak-Before-Break Benchmark Summary – Phase 1," *Structural Mechanics in Reactor Technology (SMiRT-26),* Berlin/Potsdam, Germany.

Williams, P.T., Bass, B.R., Dickson, T.L., and Klasky, H.B. (2017). "LEAPOR – A Computer Code for Leakage-Rate Calculations Cracks in Cooling Water Piping Systems," *Proceedings of the ASME 2017 Pressure Vessels and Piping Conference*, PVP2017-65263, Waikoloa, Hawaii, USA.

Zaloudek, F. R. (1963). *The critical flow of hot water through short tubes*, HW-77594, U. S. Atomic Energy Commission (USAEC), Richland, Washington, USA.