Structural mechanical and thermal hydraulic aspects on the behaviour of crack like leaks in piping

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Abstract:

The evaluation of fluid flow rates through crack-like leaks in pressurized components plays an important role for leak-before-break considerations. Thermal hydraulic and structural mechanical analyses were performed for a postulated leak in the surge line (SL) of a PWR type Konvoi under design basis accident conditions. The leak was postulated in form of a circumferential through-wall crack of 180 degrees length. The size of the leak was calculated in the framework of FE-calculations with the code ADINA using an analysis model of a cooling loop of type Konvoi. With the calculated leak size, an ATHLET calculation was conducted, also examining the influence of the consideration of a variable leak size. In the investigated case the implication of the decreasing leak size, especially on the pressure distribution, cannot be neglected. The reduction of the leak area due to both the pressure and temperature decrease in case of a leak assumed approximately in the middle of the surge line between both connection points to the hot leg and the pressurizer amounts in the transient examined to ca. 25 % after about 1 h and leads therefore also to an approximately 33 % smaller leak rate.

Concerning the determination of the leak rates as critical flow-through rates with simplified methods according to Pana and the CDR-model (critical discharge) of the ATHLET code, good agreement has been achieved although the approaches differ considerably in parts. Relevant influence factors are the assumptions for the treatment of inflow losses in the crack channel, the consideration of the leak area in connection with the hydraulic diameter and the assumptions on the flow resistance coefficient due to the roughness of the crack surfaces.

1 INTRODUCTION

A pressure decrease during a loss of coolant accident, caused by a crack-like leak or break of piping, will generally result in changes of the local physical quantities within the leak area as well as the global system parameters like pressure and temperature in the pressure-retaining boundary. In the present simulation of such loading conditions, independent of each other, the opening areas based on the operating conditions at leak formation respectively postulated leaks will be calculated by the structural mechanic and the leak mass flows as well as the time-dependent changes of pressure and fluid temperature by the thermal hydraulic. Thus, allowing the determination of a time-dependent change of leak size due to altering parameters with suitable Finite-Element (FE) analysis models.

In thermal hydraulic calculations, the practice so far has been to apply initial leak sizes with a thermal hydraulic equivalent diameter that is constant over time at selected positions in the cooling circuit. A differentiated reflection of the location-dependent differences and the time-dependent change has not yet been considered. If a compressible fluid flows from a container through a flow passage (leak, piping, orifices, etc.) into another container (respectively into the environment), the mass flow increases initially at constant pressure in the area of the inlet side into the flow passage and with decreasing pressure in the area of the outlet side up to a maximal value, the critical mass flow; thereby reaching the velocity of sound at the tightest position of the flow passage or at its downstream ending, resp.. In case of a two-phase discharge flow, a critical mass flow is also observed as well as in the case of a discharge flow of an almost incompressible fluid (e.g. water), if along the flow path, the pressure becomes considerably smaller as the fluid temperature corresponding saturation pressure. The understanding of the critical phenomena is complicated further by thermal dynamic and fluid dynamic non-equilibrium processes, mainly depending on the geometry of the flow passage and the flow condition at the flow passage inlet [1].

The flow rates will be described normally with one-dimensional models as e.g. the models by Moody [2], Pana [3], Henry [4], the CDR-model (critical discharge) [5] or the phenomenological model by Müller [6]. The flow models differ in regards to the assumptions of the flow regime and the thermal hydraulic conditions and the consideration of the specific geometry of the crack opening. Thus, the programs show with equal input data partly strongly diverging results [7].

Due to the advanced development of Finite-Element (FE) programs for structural mechanic issues and Computational-Fluid-Dynamic (CFD) programs as well as the constantly increasing processing power during the last few years, analysis tools are now available enabling the computation of the leak opening and leak discharge and detailed distributions of essential thermal hydraulic parameters in the crack area in a three-dimensional fashion. If these analysis programs, normally independent from each other, will be coupled in a suitable way, it would provide the possibility of taking into account the mutually influencing interactions.

If the boundary conditions during a loss of coolant accident would effectuate that the leak opening area will not change significantly, then no coupling is necessary. This would for instance be the case of a 2A-break in a piping, since the leak area does not change over time; in contrary to subcritical crack-like leaks with relatively small leak openings. Here, it is expected that a detailed consideration of local conditions effects a noteworthy reduction of the discharge flow rate. This is of safety-related importance since in the frame of the assessment of a break preclusion for pressurized components, especially for the leak-before-break assessment, it is required to detect subcritical cracks in due time and reliably by means of a leak detection system. Whether a crack-like leak can be detected on time depends mainly on the actual flow rate.

Therefore, for leak rate calculations in the frame of the break resistance assessment, it has to be ensured, that the actual leak rate in case of application will be rather underestimated. This can be achieved with available simplified methods for the estimation of critical discharge flow rates through a suitable resistance coefficient. Terms of reference are shown in KTA 3206 [8]. The question, whether in case of application the critical discharge flow will be reached or whether a subcritical flow exists can only be assessed within the frame of refined thermal hydraulic analysis methods.

2 BASICS FOR LEAK RATE CALCULATIONS

The computational or experimental determination of discharge flow rates through crack-like leaks in pressurized components was a major focus of investigation especially in the 80ties and 90ties. The complexity of the thermal hydraulic processes of the discharge of subcooled water through a crack-like leak is illustrated in Fig. 2.1.

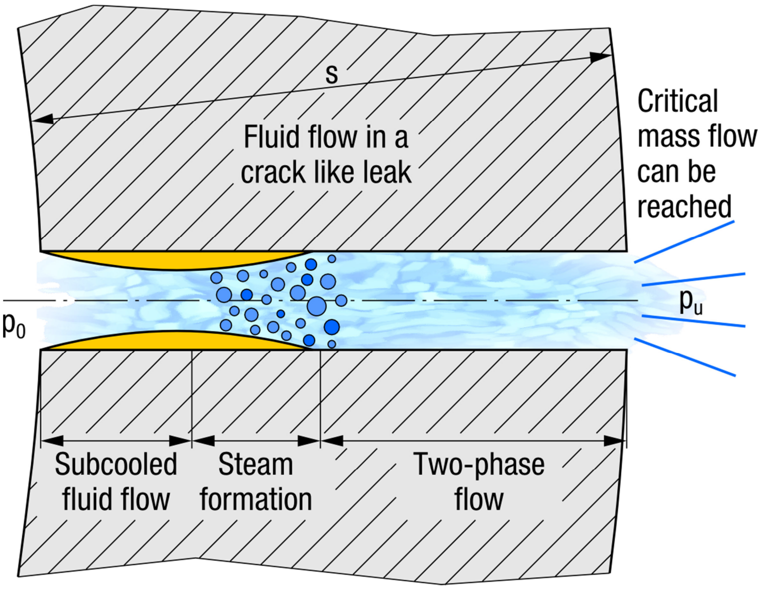


Fig. 2.1: Schematic presentation of the discharge flow through a crack

The total pressure loss along the flow path through the crack composes of the sum of inlet pressure loss, acceleration pressure loss and friction loss owing to the crack surface roughness while usually the outlet pressure loss can be neglected. The relative extension of the different regions are strongly dependent on the leak area, the hydraulic diameter, the wall thickness and the subcooling of the fluid at the inlet side of the flow passage. In the left part of Fig. 2.1, the flow is strongly constricted in comparison to the cross section. In case of pressurized water conditions the originally subcooled fluid turns into saturated steam under consideration of the inlet pressure loss. In the middle part of the wall, increasingly steam arises. The pressure loss in the right part of Fig. 2.1 is characterised by the crack surface roughness as well as by acceleration losses caused by evaporation and the decrease of vapour density due to pressure decrease.

In the calculation concept of Pana [9], various calculation methods are applied depending on the thermal dynamic condition of the fluid flowing through the crack.

Investigations of Pana ([3], [9]) indicate that a final pressure p_2 is reached at the discharge of subcooled water flowing through a crack, corresponding approximately to the saturation pressure of the fluid temperature prior to entering the flow path (stagnation temperature), i.e.

$$p_2 = p_S(T_0)$$

Presuming the pressure gradient pushing the mass flow is the difference between stagnation pressure and pressure p_2 arising at the discharge position, the result for the mass flow density G (leak rate divided by leak area) according to the “modified Bernoulli-equation” is:

$$G = \sqrt{\frac{2 \cdot [p_0 - p_S(T_0)] \cdot \rho_S(T_0)}{1+\zeta}}$$

$\rho_S(T_0)$ – saturation value of fluid density at stagnation temperature
ζ – flow resistance

The flow resistance reads as follows:

$$\zeta = \zeta_{in} + \lambda \cdot \frac{t}{d_h} + \zeta_{out}$$

While the inlet part ζ_{in} according to [10] is normally presumed to be 0.5 and the ζ_{out} can be neglected, the friction term is calculated from the resistance coefficient λ, the wall thickness t (flow length) and the hydraulic equivalent diameter d_h.

$$d_h = 4\,A/U$$

with A – leak area, U – leak circumference

3 GRS CODE WINLECK

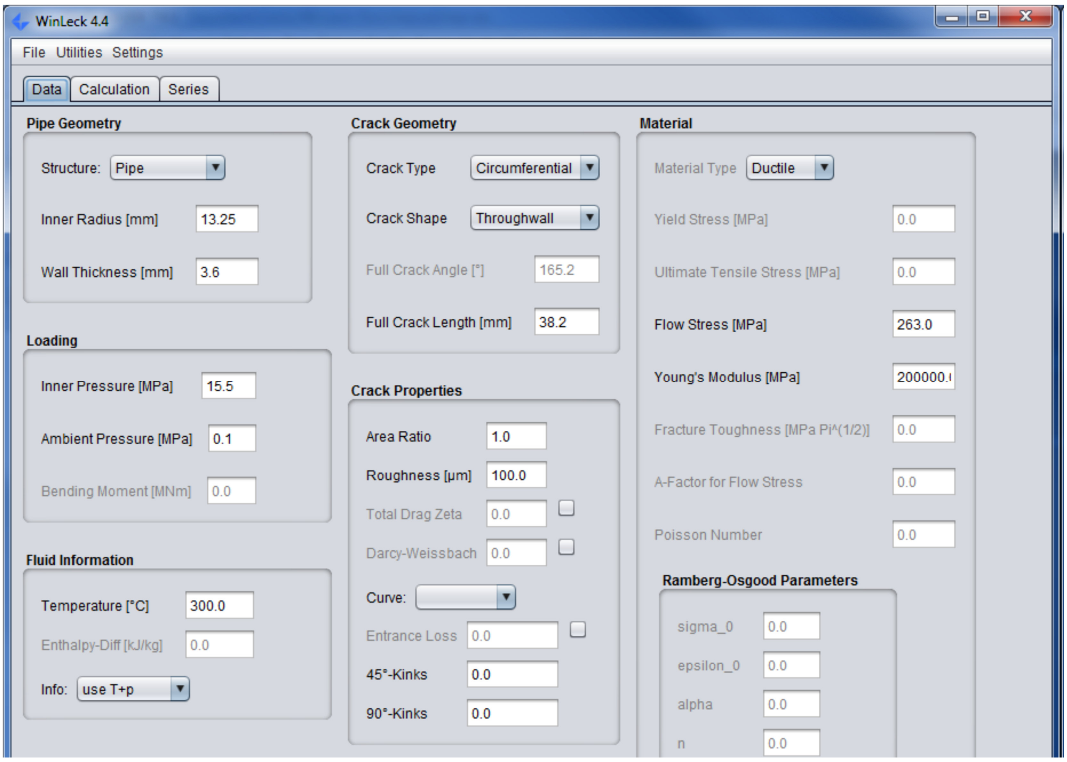
To ease the handling of simplified structural mechanical methods and leak rate calculation methods, the interactive computer program WinLeck has been developed in order to use various methods on a common basis. The program contains models for the determination of leak areas of through-wall cracks and possibilities for leak rate calculations with the Henry- and Pana-model as well as 4-factor-equation by Müller. Furthermore, the program allows the estimation of critical crack lengths for through-wall cracks in both circumferential and longitudinal direction in piping and failure pressures of piping with surface cracks.

The newest version of WinLeck has been programmed in Java and is therefore more flexible than the original Visual Basic version. The platform-independence of Java enables the executability of WinLeck on diverse hardware and the portability onto current and future operating systems without any changes to the program code. In regards to future extensions of the WinLeck program, the advantages of the object orientation and parallelisation of calculation routines in Java are worth mentioning. In this connection, the calculation routines of leak area and leak rate calculations created with Fortran programs are also worthy of mention. Fig. 3.1 to Fig. 3.3 depicts the input template of the new WinLeck version. The input template 1 (Fig. 3.1) gathers the input data of pipe geometry, loading, material property values, material behaviour and crack shape.

With the template shown in Fig. 3.2, methods for the calculation of leak area and leak rate can be selected. In total, three methods are available for the leak area calculation: Fracture-Mechanic-Handbook [11], Wüthrich [12] and Siemens KWU [13]. Additional data of the Ramberg-Osgood constants for the calculation of critical crack lengths, gathered in the input template (see Fig. 3.1), can only be considered from the calculation method of the leak area according to [11]. Possible methods for the leak rate calculation refer to methods according to Henry [4], Pana [3] and Müller [6].

Fig. 3.3 presents the menu for parameter studies, i.e. a parameter can be varied in an interval while the other parameters remain constant. Calculated values for leak areas and leak rates are written into a specified output file, exclusively taking into account only methods for leak area- and leak rate calculation selected priorly.

The capabilities of WinLeck (version 4.4.) were summarised in the User Handbook [14]. The program is freely available to external users under the consideration of the GRS guidelines for code transfers.



Pipe Geometry

Structure: Pipe
Inner Radius [mm] 13.25
Wall Thickness [mm] 3.6

Loading

Inner Pressure [MPa] 15.5
Ambient Pressure [MPa] 0.1
Bending Moment [MNm] 0.0

Fluid Information

Temperature [°C] 300.0
Enthalpy-Diff [kJ/kg] 0.0
Info: use T+p

Crack Geometry

Crack Type Circumferential
Crack Shape Throughwall
Full Crack Angle [°] 165.2
Full Crack Length [mm] 38.2

Crack Properties

Area Ratio 1.0
Roughness [µm] 100.0
Total Drag Zeta 0.0 ☐
Darcy-Weissbach 0.0 ☐
Curve:
Entrance Loss 0.0 ☐
45°-Kinks 0.0
90°-Kinks 0.0

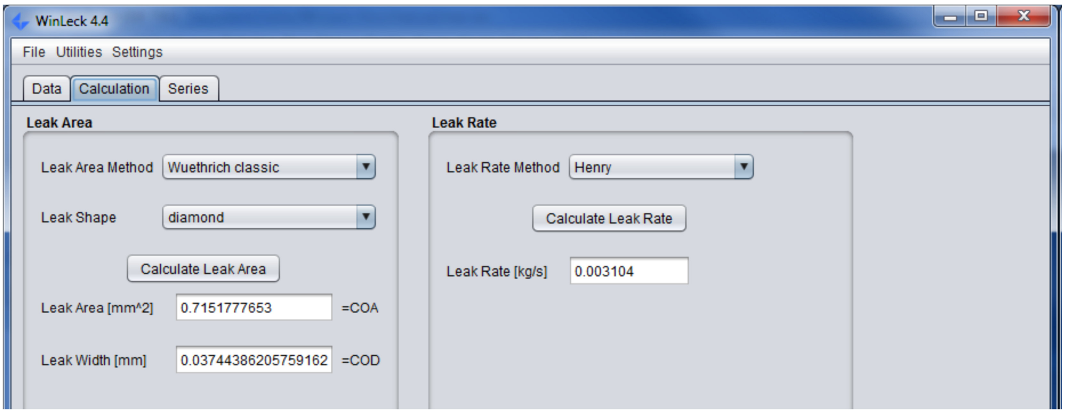
Material

Material Type Ductile
Yield Stress [MPa] 0.0
Ultimate Tensile Stress [MPa] 0.0
Flow Stress [MPa] 263.0
Young's Modulus [MPa] 200000.(
Fracture Toughness [MPa Pi^(1/2)] 0.0
A-Factor for Flow Stress 0.0
Poisson Number 0.0

Ramberg-Osgood Parameters

sigma_0 0.0
epsilon_0 0.0
alpha 0.0
n 0.0

Fig. 3.1 Menu for input data in WinLeck (Version 4.4)



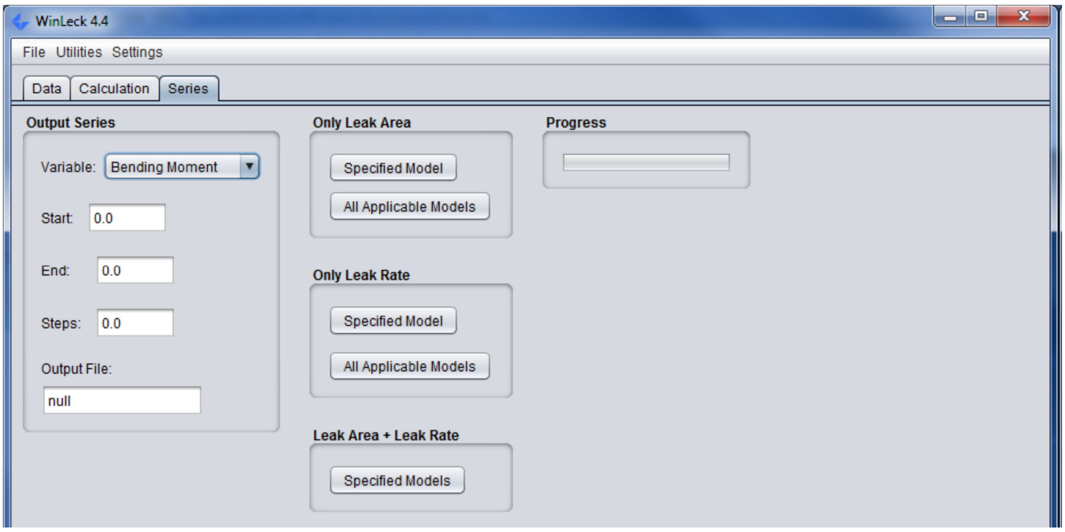
Leak Area

Leak Area Method Wuethrich classic
Leak Shape diamond
Leak Area [mm^2] 0.7151777653 =COA
Leak Width [mm] 0.03744386205759162 =COD

Leak Rate

Leak Rate Method Henry
Leak Rate [kg/s] 0.003104

Fig. 3.2 Menu for calculations in WinLeck (Version 4.4)



Output Series

Variable: Bending Moment
Start: 0.0
End: 0.0
Steps: 0.0
Output File: null

Fig. 3.3 Menu for parameter studies in WinLeck (Version 4.4)

4 THERMAL HYDRAULIC AND STRUCTURAL MECHANICAL ANALYSES OF A POSTULATED LEAK IN THE SURGE LINE

For the determination of the behaviour of a PWR primary coolant loop of type Konvoi at a postulated through-wall crack in the surge line (SL), calculations were conducted with the thermal hydraulic program ATHLET [15] and the structural mechanical program ADINA [16], whereby a crack-like leak was postulated in the surge line. Fig. 4.1 displays the applied ATHLET-model for the leak in the middle of the surge line between its connection to the reactor coolant line and the pressurizer. The postulated leak position in the ATHLET model of the surge line is depicted in Fig. 4.2.

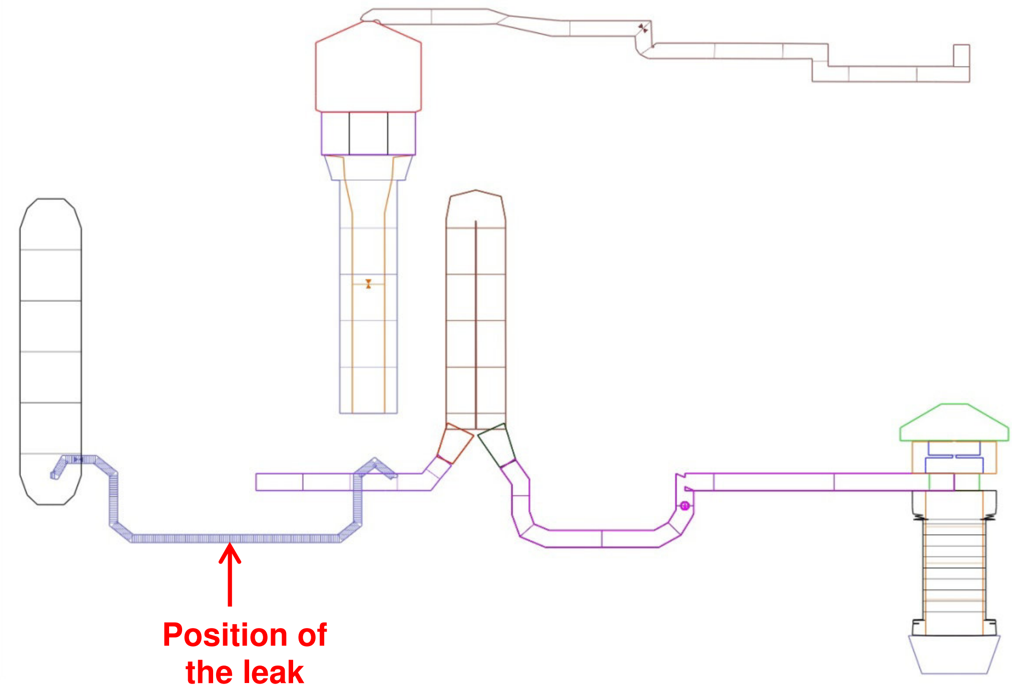


Fig. 4.1 Nodalisation of components in primary coolant system

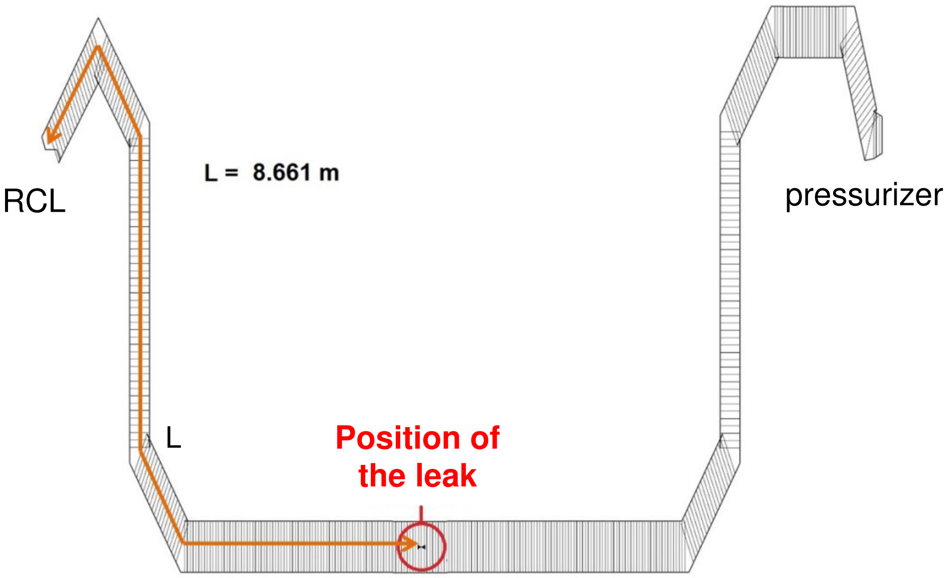


Fig. 4.2 ATHLET analysis model of the surge line and position of the postulated leak (L distance from the reactor coolant line)

The size of the postulated crack-like leak was determined within the frame of structural mechanical calculations with the Finite-Element (FE) model of the coolant loop (see Fig. 4.3) under operating conditions. At the respective leak position, a circumferential through-wall crack with 180° length in the circumferential direction was presumed.

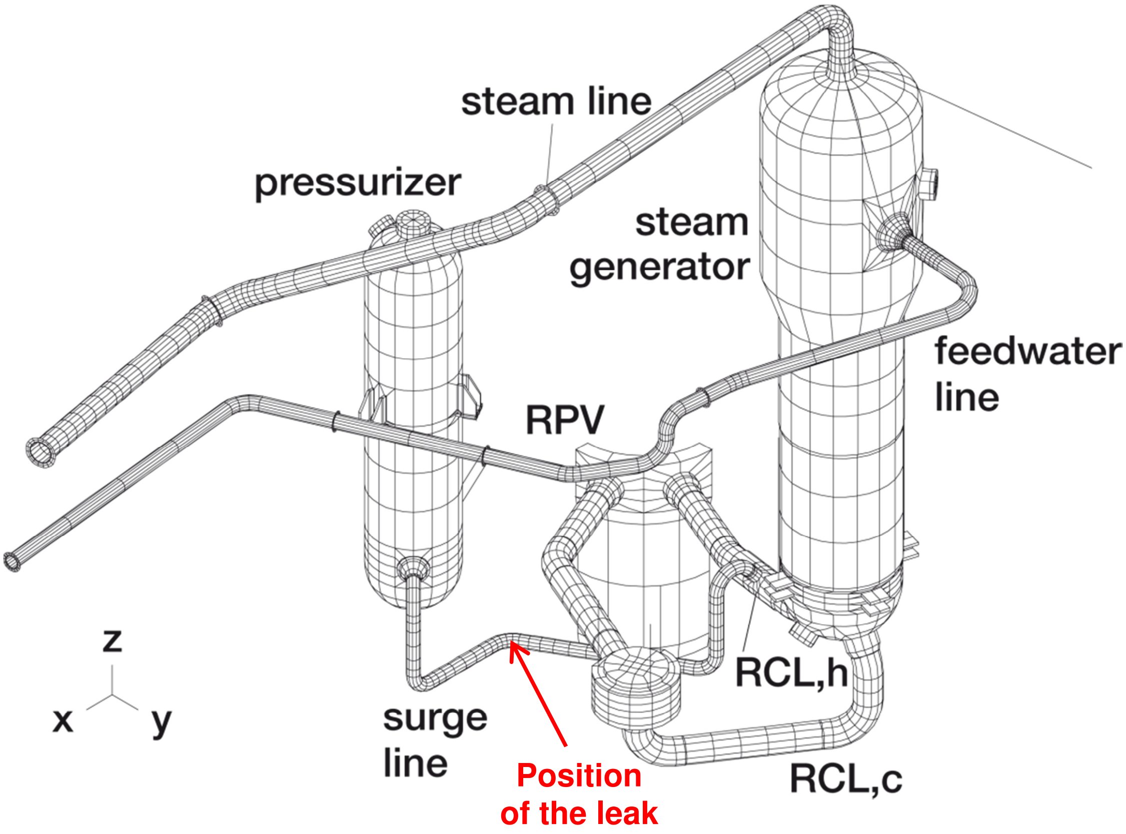


Fig. 4.3 FE-model of the coolant loop including surge line and pressurizer and the position of the postulated leak

Fig. 4.4 features the respective section in the area of the postulated leak position and the leak area A_i calculated at the inside of the pipe wall. The opening of the leak occurs during operating condition in 15 ms due to the guidelines of the Reactor Safety Commission. Afterwards, the leak opening area is assumed to be constant and also changing, since the leak opening area can alter in consequence of the pressure and temperature drop during a leak transient

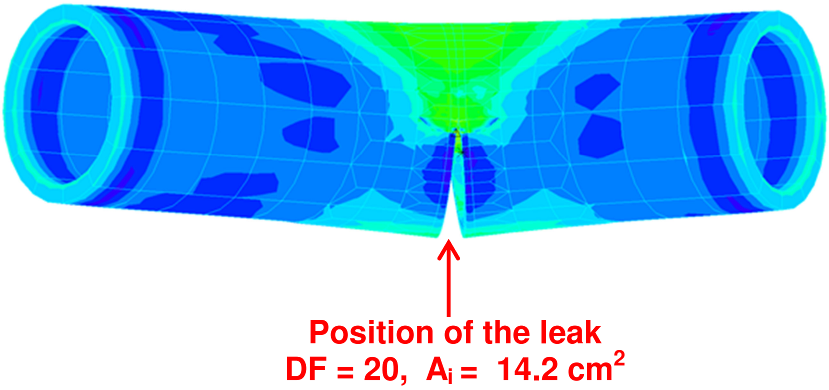


Fig. 4.4 Section of ADINA surge line model in the area of the postulated crack-like leak with deformation during operating load (DF - deformation factor, A_i leak area inside)

In the following the analysis results are summarised. Fig. 4.5 shows the time history of the pressure on the primary side and the fluid temperature in the area of the leak. The leak scenario shows that 30 s after opening of the leak the reactor emergency shut-down and the turbine trip takes place. The high pressure injection starts at ca. 935 s, when the primary pressure reaches 11 MPa. At the beginning of the transient, i.e. at normal operating conditions (point in time 600 s), the leak has a size of 14.2 cm^2 at the inner surface of the pipe. With the pressure and temperature distributions in the loop calculated for the constant leak areas (CLA), the change of the leak area was computed with ADINA using the FE-model (see Fig. 4.3 and Fig. 4.4). The result (see Fig. 4.6) reveals that the leak area inside decreases from initially 14.2 cm^2 in about 1 h by approximately 25 %. Due to inertial effects considered in the elasto-plastic dynamic ADINA calculation the opening of the leak in 15 ms results in a small peak-wise increase of the leak size close to time point 600 s. With the varying leak area (VLA), a further ATHLET calculation was performed. The results of the primary pressure and the fluid temperature near the leak are compared with the constant leak calculation (see Fig. 4.5). It shows that the pressure difference after about 1 h is about 0.74 MPa, i.e. ca. 8 %.

In the leak rate calculation with simplified methods according to Pana, stationary conditions are assumed for the respective calculation points of time. The calculation has been conducted with the leak area at the internal surface, approximated through a rectangular leak cross section. At the beginning of the transient, the leak has a total crack length of 547 mm and a crack opening of 2.6 mm, i.e. a hydraulic diameter of ca. 5.2 mm and a leak area of about 14.2 cm^2. The crack surface roughness is predefined at 10 µm in the calculations according to the statements in KTA 3206 for austenitic piping.

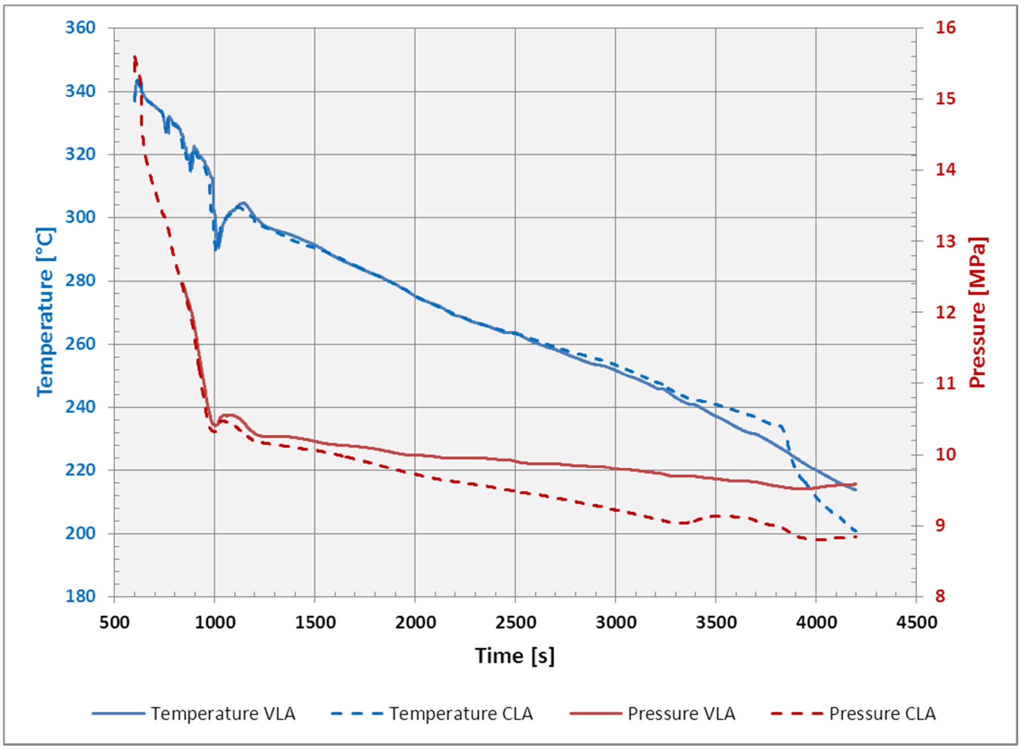


Fig. 4.5 Temperature and pressure distribution at leak position during the leak transient with constant and varying leak area (CLA / VLA)

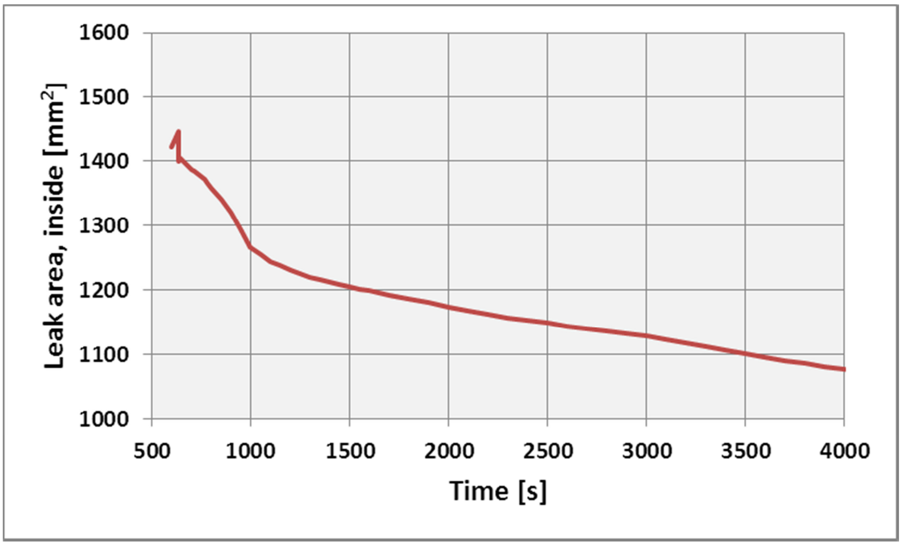


Fig. 4.6 Leak area inside during leak transient (position 2)

Fig. 4.7 presents the results of the leak rate calculations with the Pana and the CDR models in the case of constant leak area in comparison to the case of variable leak area. After opening of the leak the undercooling of the fluid at the inlet side of the leak first disappears, i.e. the fluid is saturated and steam is formed partly. Together with the strong pressure decrease this effects a decreasing leak rate. After about 1200 s the undercooling of the fluid increases which effects an increase of the leak rate. Further it becomes obvious that the leak area reduction due to pressure and temperature decrease has a major effect on the leak rate which after approximately 1 h transient period of time is nearly 33 % smaller than in the calculation with constant leak area.

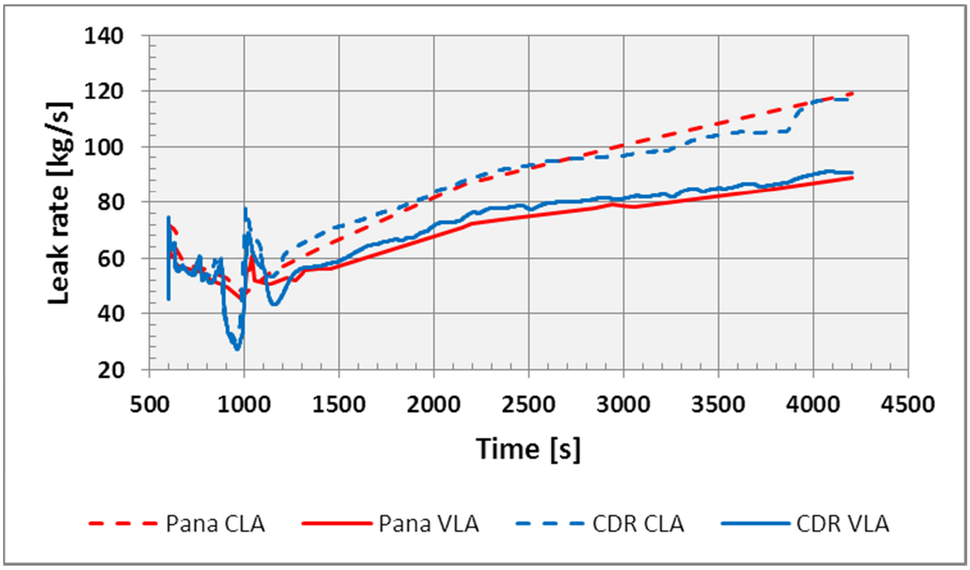


Fig. 4.7 Calculated leak rates for constant and decreasing leak area

Furthermore, Fig. 4.7 shows a good agreement between the results of the two leak rate models which are in parts very different. More details on the calculations and the results of other leak positions as well as numerous calculations of leak rate experiments are given in [17].

5 SUMMARY AND OUTLOOK

The evaluation of fluid flow rates through crack-like leaks in pressurized components plays an important role for assessments of break preclusion, especially the leak-before-break assessment step.

In the framework of this paper, various calculation methods for the simulation of structural mechanical and thermal hydraulic phenomena due to flows through crack-like leaks in the coolant loop have been examined, especially the effect of the changing leak size due to the pressure and temperature decrease. Main result is, that in the presented case of a crack-like leak in the middle of a surge line under design basis accident conditions, the leak area is reduced by ca. 25 % after about 1 h which leads to an approximately 33 % smaller leak rate.

In the application case, leak detection has to be ensured. Therefore, the calculated leak rate has to underestimate the real leak rate with respect to the measuring range of a leak detection system. By using available simplified methods for the estimation of critical discharge flow rates, a suitable resistance coefficient has to be chosen. Some guidelines based on evaluation of leak rate experiments are given in KTA 3206 [8] based on the investigations given in [18]. The question, whether in case of application, the critical discharge flow will be reached or whether a subcritical discharge flow exists, can only be assessed within the frame of refined thermal hydraulic analysis methods. Therefore, in an advanced step, the discharge flow from crack-like leaks is to be simulated in more detail, e.g. with the computer program ATHLET [15].

Further, more detailed examinations should be conducted in how far CFD-methods for leak rate calculations can be applied. For first validation calculations with ANSYS CFX [19], tests were chosen with discharge flows through a Venturi orifice [20]. Initially, postcalculations were performed for tests with single-phase discharge flows [17]. In a further step, tests with a two-phase discharge flow were looked at. The postcalculation of a single-phase discharge flow showed a satisfactory agreement between calculation results and appropriate measured data. In regards to the two-phase discharge flow, no satisfying agreement between calculation and test could be obtained despite various analysis models with different element sizes have been used. Therefore, it seems that the model approach, available in CFX for the simulation of abrupt evaporation of an overheated fluid caused by a pressure decrease (flashing), should be further developed to simulate the two-phase discharge flow from crack-like leaks [17].

Against this background, in a next step, the two-phase discharge flow should be first simulated with an ATHLET model, which approximates the change of thermal hydraulic quantities along the flow path. Further advancement in the validation of complex analysis methods for the determination of leak rates can be attained if well instrumented leak rate tests of discharge flows through crack-like leaks will be conducted.

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ABBREVIATIONS

ADINA	Automatic Dynamic Incremental Nonlinear Analysis
ATHLET	Analysis of the Thermal hydraulics of LEaks and Transients
CDR	critical discharge
CFD	computational fluid dynamics
CLA	constant leak area
FE	finite element
SL	pressurizer surge line
PWR	pressurized water reactor
RCL	reactor coolant line
RPV	reactor pressure vessel
VLA	variable leak area