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FRACTURE MECHANICS ANALYSIS OF REACTOR PRESSURE VESSEL FOR EMERGENCY CORE COOLING WITH ASYMMETRIC COOLING AND FLUID-FLUID MIXING

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ABSTRACT

The safety analysis of a reactor pressure vessel is based on materials analysis, thermal hydraulic analysis and fracture mechanics analysis. This safety analysis is shown as an example for emergency core cooling with asymmetric cooling and fluid-fluid mixing. The thermal hydraulic analysis is based on the definition of the scenarios, the relevant tests and the improved calculations. The fracture mechanics analysis is performed with finite element calculations for temperature and stresses and with analytical calculation for stress intensity factors.

1 INTRODUCTION

The operational load situations during accident conditions are dominated by pressure and temperature transients during an emergency core cooling (ECC) event following a loss of coolant accident (LOCA) relevant for pressurized thermal shock (PTS).

The behavior of the reactor pressure vessel (RPV) under these accident conditions is evaluated by means of fracture mechanics. The application of the fracture mechanics method is based on the fact that an existing crack remains stable and brittle fracture will not occur as long as the stress intensity factor (K_I) (caused by acting stresses on an existing / postulated crack) is smaller than the critical stress intensity factor (K_{Ic}), Fig. 1 according to the KTA-rule [1].

2 LOSS OF COOLANT ACCIDENT

ECC occuring during a hypothetical pipe break (e.g. small break, SB-LOCA) results in a thermal shock generating thermal stresses in the RPV wall. The effect of these stresses on postulated defects has to be shown, calculating the relevant stress intensity factor as a function of temperature. The accuracy to determine the stress intensity factor resulting from thermal shock depends on the exact knowledge of pressure and temperature transients acting at the vessel wall in the course of the event. Assuming that the actual temperature of the ECC water is acting at the RPV wall is a common simplification which leads to conservative results [2]. In this paper the evaluation of the safety against brittle fracture is performed taking into account mixing effects of cold ECC water and the hot coolant in the main coolant line and in the RPV itself.

3 THERMAL HYDRAULIC ANALYSIS

3.1 SELECTION OF RELEVANT TRANSIENTS

The criterion for the selection of the relevant transients refers to the coolant water in the downcomer. The relevant parameters are:

- decrease of the global temperature niveau
- cooling rate of the water
- amount of internal pressure
- distribution of the temperature
- heat transfer coefficient α in azimuthal direction.

Most relevant for temperature induced stresses in axial direction are the minimum temperature and the maximum α-values in the plume and the maximum temperature and the minimum α-values outside of the plume.

3.2 SYSTEM CALCULATIONS OF THE PRIMARY SIDE

System calculations performed with the RELAP-Code are used to determine the primary side system transients following a postulated PTS-relevant LOCA. The system pressure, the coldside ECC-injection rate and temperature and the mean downcomer fluid temperature are boundary conditions for the determination of the fluid temperature distribution in the downcomer.

3.3 FLUID-FLUID-MIXING (FFM) SCENARIO

Several FFM-experiments were performed to quantify the thermal mixing in the cold leg and downcomer. Of greatest importance are the tests performed at CREARE, at HDR and at UPTF, for more information see [2].

A "cold stream" originates with the high pressure injection plume at the point of injection, continues towards both ends of the cold leg, and decays away as the resulting plumes fall into the downcomer and pump/loop-seal regions. A "hot stream" are in counterflow arragement to a cold stream supplying the flow necessary for mixing. The above FFM-scenario applies when the primary system is filled with water at least up to the upper edge of cold leg.

Steam condensation on a subcooled ECC water plug or steam condensation on the subcooled ECC-water jet and on a subcooled water layer between injection port and downcomer determine the water temperature at the cold leg/downcomer interface in case of a partly steam filled cold leg.

Typical results gained with the SIEMENS-FFM Code "F-Mix" concerning the cold leg cold stream temperature and the axial cold water plume temperature and α-value distribution in the downcomer (below cold leg midline) for a SB-LOCA in the hot leg of the primary circuit are shown in Fig. 2 and Fig.3. In this LOCA the internal pressure drops very quickly (appr. 500 s) below 5 bar.

4 CALCULATION OF TEMPERATURE AND STRESS DISTRIBUTION IN THE RPV WALL

The results of the thermal hydraulic analyses are used to determine temperature and stress distributions in the RPV wall by two and three dimensional finite element (FE) analyses.

For this purpose one half of the cylindrical RPV including cladding is modeled, so that temperature changes of the primary coolant medium in the 2D-analysis in azimuthal direction and in the 3D-analysis in azimuthal and axial direction are considered in the FE-analysis.

The analyses are performed with the ADINA program system [3], [4]. In the 2D-analysis the radial section is placed at the level of the core. For the non-steady-state temperature distribution calculation the heat transfer between RPV wall and fluid is simulated by convection elements . An adiabatic transition, i.e., dT = 0, is assumed in the axis of symmetry. The outer wall of the RPV is considered to be insulated, i.e., dT = 0 at this point as well.

For the stress analysis only the symmetry condition need to be considered, i.e. at z = 0 the displacement $u_z = 0$. For stability reasons one node is limited in the y direction. The stresses are calculated from the temperature distribution under the asssumption of linear-elastic material behavior. In the 2D-analysis plane strain condition (PSC), i.e., $\varepsilon_{ax} = 0$ is assumed.

5 FRACTURE MECHANICS ANALYSIS

KTA 3201.2 [1] specifies that the critical flaw size which is still allowable must be twice as large as a flaw size which can be reliably detected by non-destructive examination (NDE) methods. This yields, under consideration of a usual detectable flaw size of 4 mm x 20 mm to a postulated flaw depth of 8 mm with a length of 40 mm. Due to plume cooling the maximum stresses are in axial direction, therefore surface flaws in circumferential direction are analyzed in the ferritic vessel wall (cladding ignored).

The K_I-values are calculated at the deepest point (Fig. 4, point A) and at the surface (point B) using the analytical program EASY [5]. To show clearly the influence of thermal stratification, in the K_I-calculation no residual stresses are taken into account. The axial stresses due to internal pressure which are less than 5 N/mm^2 are neglected.

For the investigated points along the crack front (point A and point B) Fig. 5 and Fig. 6 show the gained K_I-pathes calculated with the stresses from the 2D- and 3D-analysis. As the 2D-FE-analysis results in higher stresses the K_I path is remarkable higher, too. The relevant location for the safety analysis in this example is Point B (3D).

6 CONCLUSION

To calculate the behaviour of a RPV under a LOCA relevant for PTS the accuracy of the temperature and also the heat transfer coefficient distribution in the azimuthal and axial direction in the downcomer is important.

Large temperature and heat transfer differences in azimuthal direction lead to considerable thermal stresses in axial direction with tensile stresses deep in the vessel wall. In most cases a 2D-FE-analysis leads to a conservative result but in a LOCA with a fast temperature change in the transient a 3D-FE-analysis may be necessary to get the correct temperature fields.

7 REFERENCES

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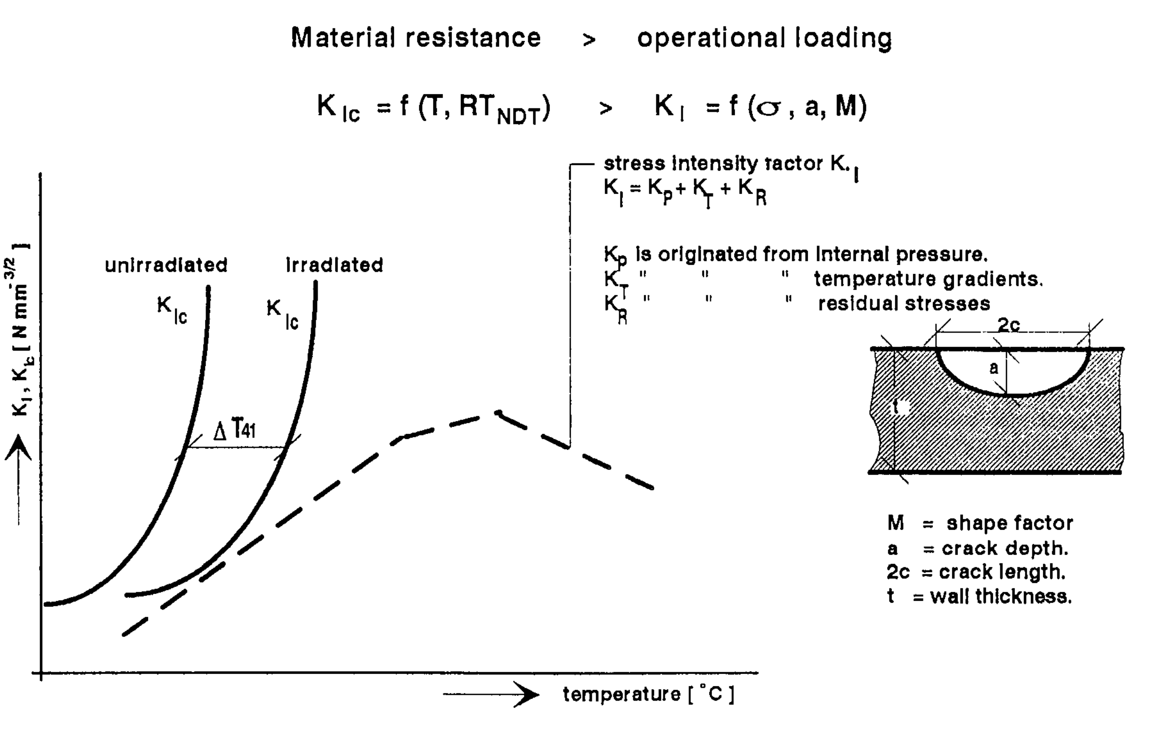
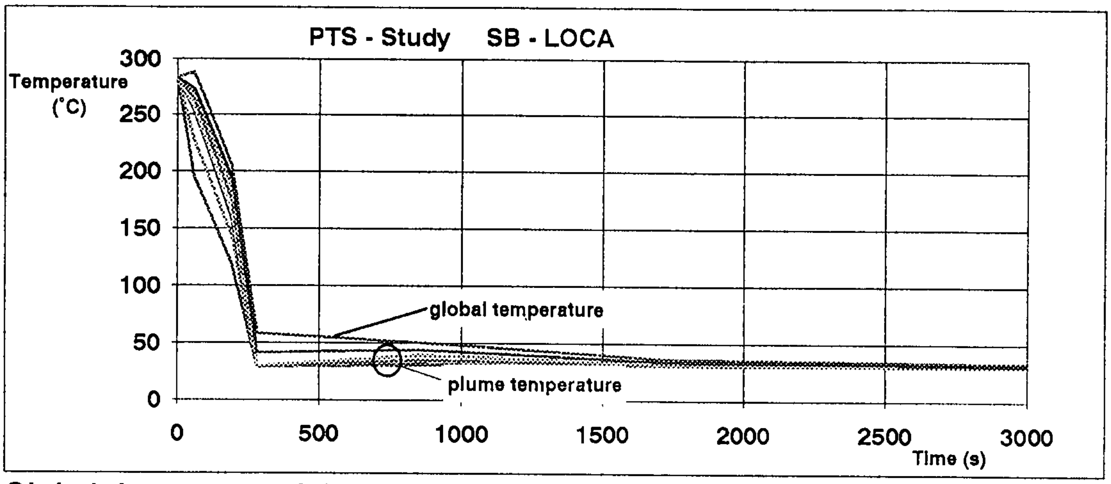
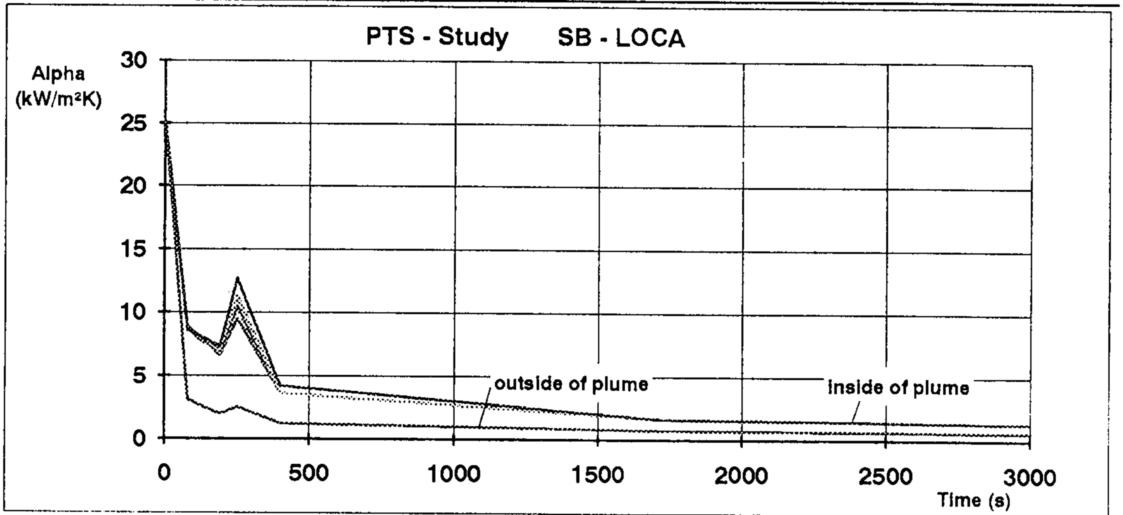


Fracture mechanics analysis, accidents.
(example: thermal shock)
Fig. 1



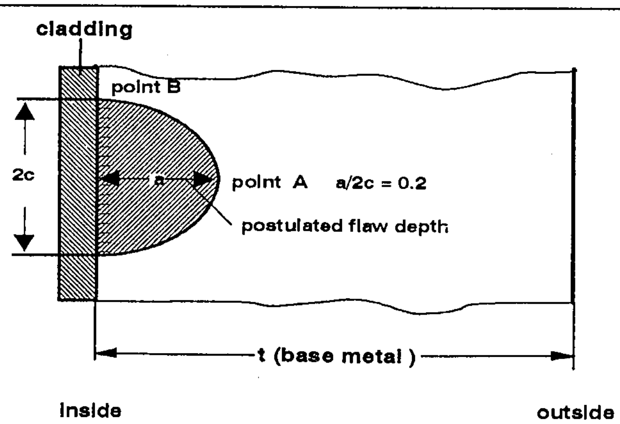
Global downcomer fluid temperature and downcomer plume centerline temperature at different distance

Fig. 2



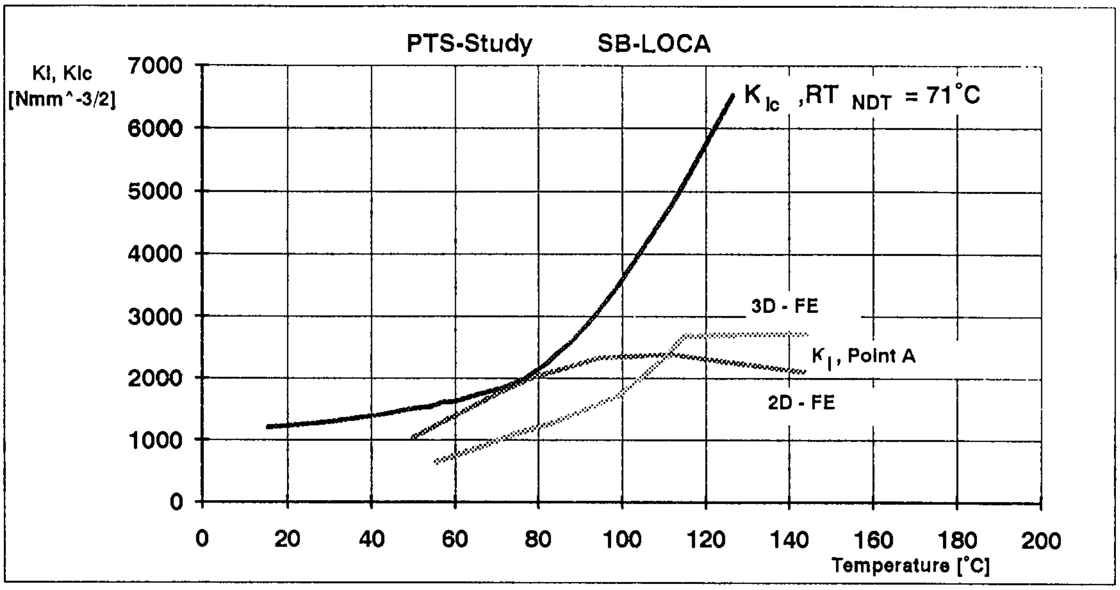
Heat transfer coefficient RPV - wall -fluid

Fig. 3



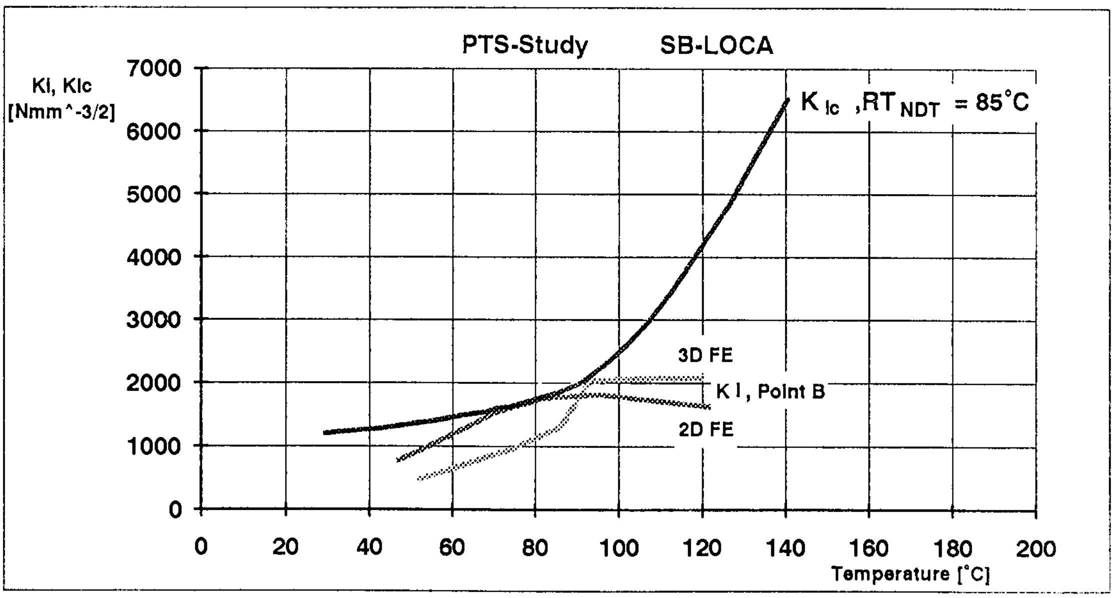
Postulated flaw in RPV

Fig. 4



K_{Ic} and K_I versus temperature for a circumferential crack, depth = 8 mm

Fig. 5



K_{Ic} and K_I versus temperature for a circumferential crack, depth = 8 mm

Fig. 6