Analysis of PWR in Case of Asymmetric Cold Water Injection

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ABSTRACT

Reactor pressure vessels are subject to detailed structural analysis for all kind of loading conditions. As a worsed case load the cooldown of the whole reactor pressure vessel to the injection temperature was assumed in many analyses. More detailed 3-dimensional calculations including asymmetric local loads caused by cold water injection are a matter of ongoing effort to quantify the margin of safety of the pressure vessel. As is shown in the analyses this type of loading can cause quite different loads at the crack tip of postulated cracks.

1. INTRODUCTION

The safety concept of light-water reactors (LWR) is based on the so called "design basis accidents". As part of the design basis accidents loss of coolant of the primary as well as the secondary circuit is postulated, assuming different leak sizes and locations and boundary conditions. The goal of the safety analysis for design basis accidents with primary or secondary blowdown is

- to demonstrate sufficient cooling of the reactor core assuming the minimum injection capability according to safety criteria and
- to demonstrate the integrity of the reactor pressure vessel (RPV) assuming the injection capability which causes the maximum load, using end-of-life (EOL) material conditions and postulated cracks of a limited size.

In the frame-work of the reactor safety research programs structure mechanics analysis methods are developed and verified by large-scale experiments. As an international effort related to this the CSNI-FAG*) Project FALSIRE should be mentioned, see also paper G02/1 of this conference.

The analysis results presented in the following chapters have been calculated with the finite element (FE) programs ADINA (1987) and ADINAT (1987). The generation of the finite element models and the result evaluation are done with suitable pre- and postprozessors.

2. BOUNDARY CONDITIONS OF THE ANALYSES

The interacting parameters for the integrity assessment based on a fracture mechanics analyses are the load pattern, the material properties and resistance as well as the postulated cracks.

2.1 LOAD CONSIDERATIONS

As a worsed case load the cooldown of the whole reactor pressure vessel to the injection temperature of the emergency core cooling water was assumed in many analyses. Using this assumption the longitudinal oriented crack seemed to get the highest load. As we have seen by the HDR-experiments (Neubrech et al. 1988) the loading pattern is more complex with respect to the crack orientation.
Depending on the principal design of the primary system (2-, 3-, 4-, 6-loops), the injection location and geometry as well as the injection mass flow rate and temperature the reactor pressure vessel wall may be subjected to a pronounced variation in temperature of the circumference as well as the vertical axis. In the HDR-experiments this situation was simulated by an in-vessel vertical cooling channel. As has been shown in the experiment this type of load results into a stress intensity at the crack tip of a circumferentially oriented crack which does increase with time as long as the cooling transient holds on. In the symmetrical load case there is a pronounced decrease in stress intensity with time.
In reality there will be some mixing between the water inside the vessel in the downcomer and the injected water. For the verification of mixing models some experiments are available. Detailed analysis showing the fracture mechanics behaviour is presented in chapter 3 and 4.

2.2 CONSIDERATIONS TO POSTULATED DEFECTS

For the assessment of pressure vessel integrity most design codes require to analyze the consequences of defects postulated up to a size of one quarter of the wall thickness. The acceptance criteria give some allowance for crack growth for combined mechanical-thermal loads at accident conditions in most of the design codes. Usually the defects are postulated in the weld region near the middle of the core where the maximum

*) CSNI-FAG: Commitee on the Safety of Nuclear Installations - Fracture Assessment Group

change of material properties take place (end-of-life conditions). For the analyses the defects are assumed as charp-edged cracks. Further consideration has to be given to the shape and location (surface or embedded) of the crack. Furthermore the influence of the orientation and size of the crack has to be evaluated. As will be shown in chapter 4 the circumferential orientation is the most significant one for asymmetric cooling transients. The work to describe the influences of these other important factors (size, location) is in progress.

2.3 CONSIDERATIONS TO MATERIAL PROPERTIES

At some loading conditions parts of the structure are stressed beyond the elastic limit. For a detailed analysis it is necessary to simulate the elasto-plastic behaviour of the ferritic material as well as for the cladding. It may be even important to include the increase of the yield stress caused by the irradiation effects in order to avoid an underestimation of the crack tip loading. As has been shown by previous investigations (Sievers et al. 1989) the physical properties (coefficient of thermal expansion etc.) have a pronounced effect too. For cladding materials the physical properties may deviate considerably from catalog values.

3. POSTANALYSIS OF HDR-THERMAL SHOCK EXPERIMENT

At the experimental facility Heißdampfreaktor (HDR) experiments concerning asymmetric cooling conditions have been performed in the pressure vessel.

In test THEL II the reactor pressure vessel of the HDR with a partly circumferential crack under normal operation conditions (internal pressure 11 MPa, RPV-water/wall temperature 305 °C) has been cooled in an artifical axial canal between an upper and a lower nozzle with 50 °C cold water (Fig. 1), Neubrech et al. (1988). The transient was finished after 20 minutes.

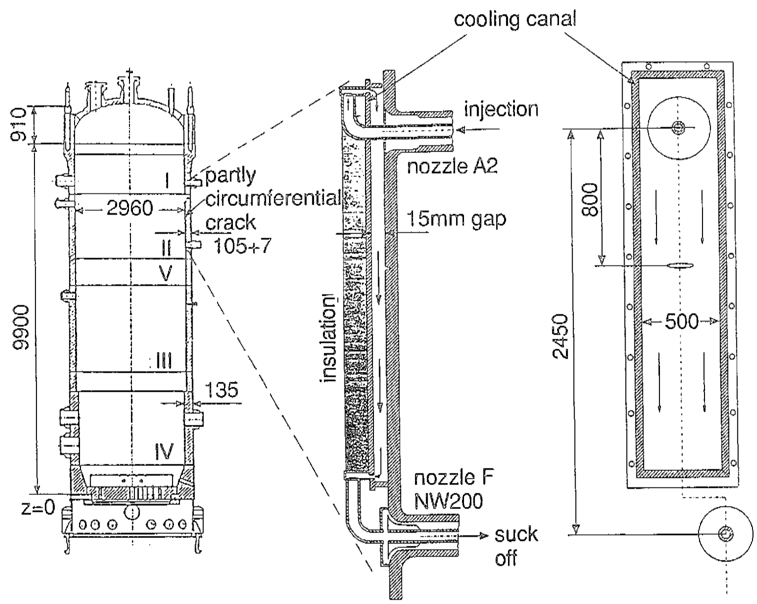


Fig. 1 :HDR-Thermal shock experiment THEL II, guided injection in RPV

The guided injection gives clear loading conditions but intensifies the loading in case of real injection because mixing effects are excluded. Before the test the investigated crack had a maximal depth of 15,5 mm and showed branching due to fractographic measurements.

Fig. 2 shows the ¼ Finite element model of the cylindrical RPV-part used in the postanalysis (Sievers et al. 1989). A summary of our precalculation results with intensified assumptions due to crack geometry and cooling conditions than realized is given in Sievers (1991).

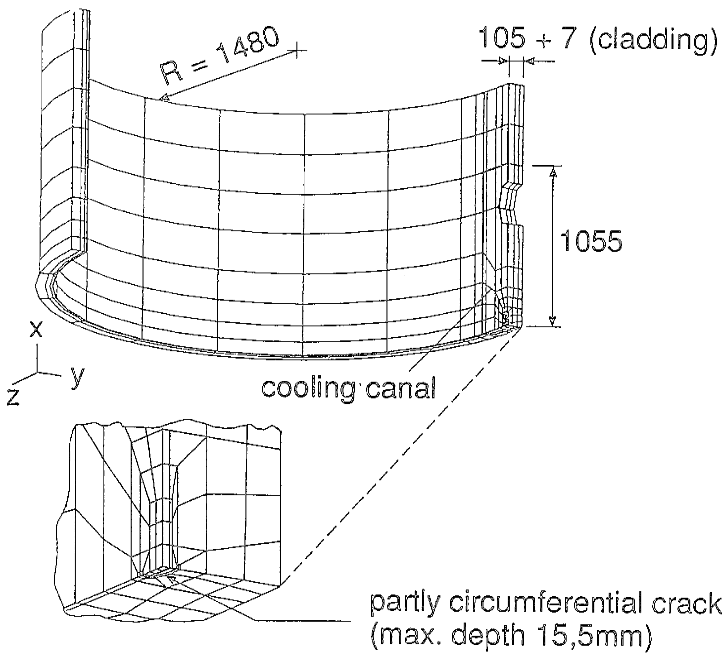


Fig. 2 :HDR-Thermal shock experiment THEL II at the RPV, 3d-Finite Element model of the cylindrical part with partly circumferential crack (postanalysis)

In that case of guided injection the axial stress, which is much higher than the circumferential component, loads the crack. The unsymmetric cooling process effects an ovalization of the cylinder with increasing tendency of plastification in the wall behind the cooling canal (Fig. 3).

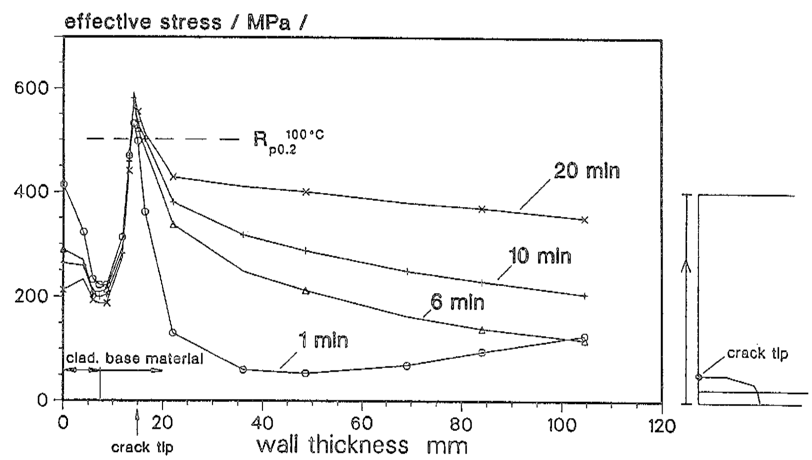


Fig. 3 :HDR-Thermal shock experiment THEL II at the RPV, effective stress in the wall with partly circumferential crack (postanalysis)

The time history of the crack-mouth-opening in comparison with the measured data is presented in Fig. 4.

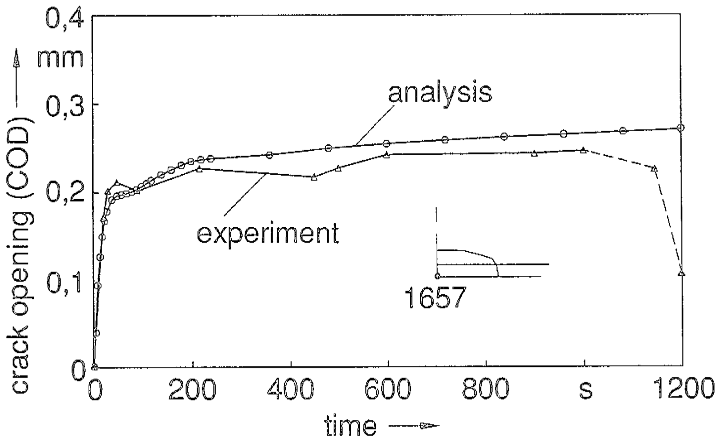
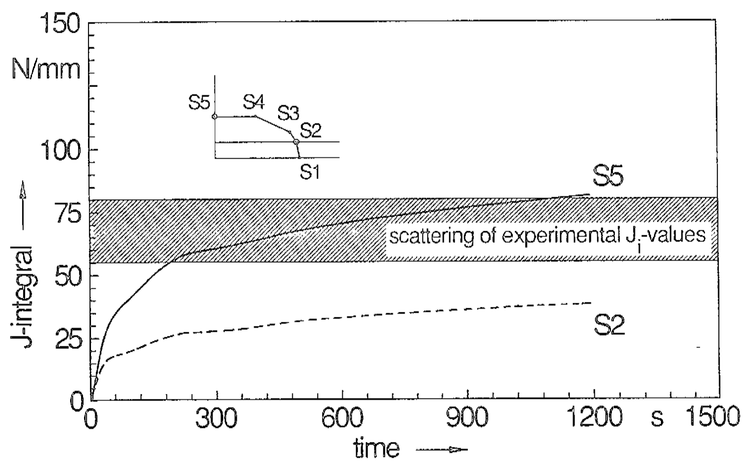


Fig. 4 :HDR-Thermal shock experiment THEL II at the RPV, crack-mouth-opening of partly circumferential crack (postanalysis)

The crack loading according to the J-integral concept calculated due to deLorenzi (1985) is shown in Fig. 5.



J-integral due to de Lorenzi:

$$J = \frac{1}{A_c} \int_V \left\{ [\sigma_{ij} \frac{\partial u_j}{\partial x_k} - W \delta_{ik}] \frac{\partial \Delta x_k}{\partial x_i} + \sigma_{ij} \frac{\partial \varepsilon_{ij}^{th}}{\partial x_k} \Delta x_k \right\} dV - \frac{1}{A_c} \int_A t_i \frac{\partial u_i}{\partial x_j} \Delta x_j \, dA$$

Fig.5 :HDR-Thermal shock experiment THEL II at the RPV, local J-integrals of partly circumferential crack (postanalysis), fracture assessment.

Characteristic of the test with strip like cooling is an increasing crack loading over a long time contrary to an axisymmetric cooling with a maximum crack loading in the first minutes dependent on the ratio of crack depth to wall thickness (Sievers 1987, 1989, 1990).
The reason is that the uncooled regions of the RPV, considering the fixities and potentiality to move, act as a frame, in which the cooled region is stretched. As long as the cooling takes place and a stationary condition is not reached the crack loading increases. The maximum J-values are calculated at the maximum depth of the partly circumferential crack and range about the crack initiation values (intersection between crack resistance curve and "blunting line") measured by compact tension specimens. Nevertheless no stable crack growth is expected because partly crack branching, which is not taken into account in the model, effects a load distribution to several crack tips. Therefore the fracture assessment based on the J-integral concept coincides with the test result, that no stable crack growth took place.

4. THERMAL SHOCK ANALYSES OF PWR RPV

For a more generic assessment parametric analyses are necessary due to uncertainties in the loading conditions, in the assumptions concerning postulated crack geometry and the material properties/crack resistance. Fig. 6 shows FE-models of a PWR-RPV and sector models with postulated cracks, which are suitable for doing parametric studies.

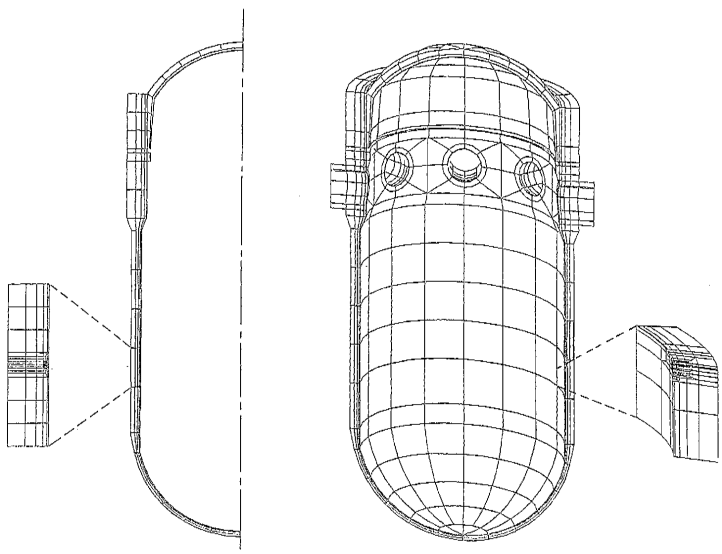


Fig. 6 :RPV-1 finite element global and sector models with (partly) circumferential crack

For a fracture mechanical analysis based on the J-integral concept the nodal point displacements and temperatures calculated in the global model have been transfered to the corresponding surfaces of the sector model as loading.

Analytical formula to determine the stress distribution due to axial cooling strips and also the stress intensity factors of different cracks are used in addition to the FE-analyses.

Objective of these analyses is to point out the influence of dominant factors, which act upon fracture mechanics results and to investigate the reliability and accuracy of the analysis methods used. Several parameters which influence the material toughness and the loading conditions due to cold water emergency injection are varied related to space and time.

In the case of high pressure emergency cooling into the hot legs the cold water decreases the temperature of the cooling fluid due to mixing. Therefore no extreme thermal shock is expected. Results of a parametric study in the axisymmetric FE-global/sector model with variation of the cooling fluid temperature (T_C) are shown in Fig. 7.

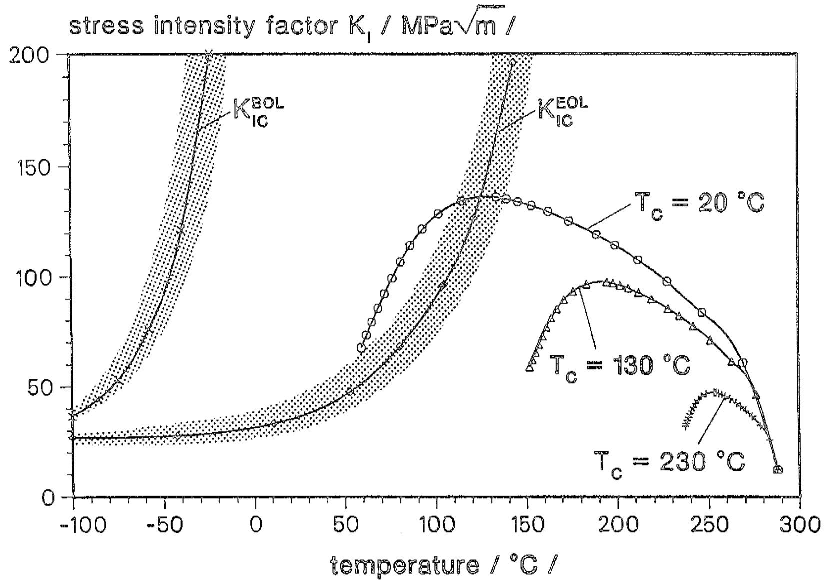


Fig. 7 :RPV-1 (axisymmetric model) with high pressure injection and variation of cooling temperature T_C, stress intensity factor of a circumferential crack (a=17 mm) versus crack tip temperature

The stress intensity factors of a circumferential crack (depth 17 mm) versus crack tip temperature are compared with the BOL*)- and approximated EOL*)-material toughness curves. The case T_C = 20 °C is excluded due to technical changes in the plant system considered.

In the case of low pressure emergency cooling (water 20 °C, 2 MPa) Fig. 8 shows the effective stress distribution versus wall thickness in the region of the weld nearby the core for different time steps after start of the loading transient due to strip like or axisymmetric cooling.

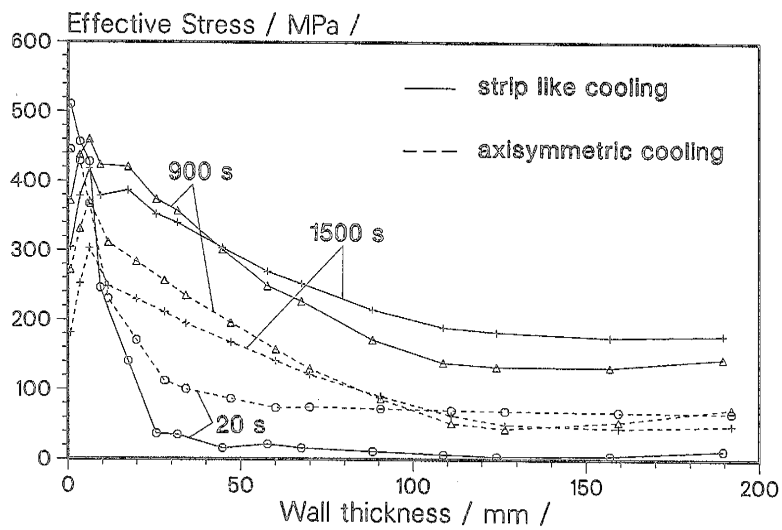


Fig. 8 :RPV-1 with cold water injection at low pressure, effective stresses due to strip like/axisymmetric cooling without crack

With axisymmetric loading high stresses are calculated only in the first minutes at the inner surface. In contrary strip like cooling effects higher loading through the wall in the cooled region as long as the cooling takes place and no filling level is built up. The possibility for a free movement in the lower part of the vessel effects that the stretching of the cooled strip may be weakened (see Fig. 9).

*) BOL/EOL: begin/end of life

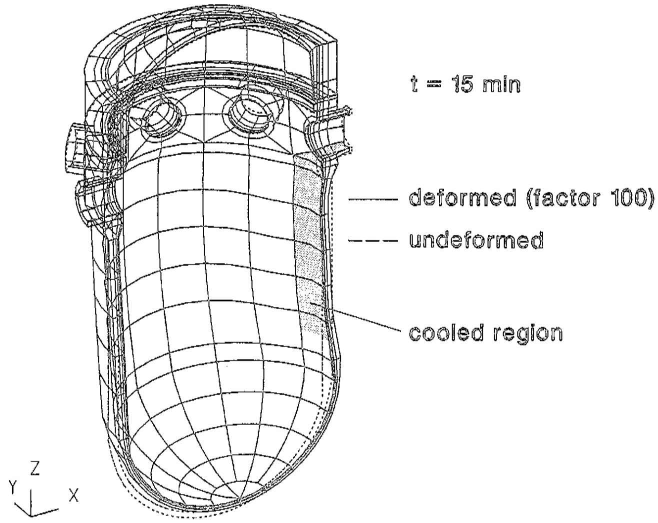


Fig. 9 :RPV-1 with cold water injection at low pressure, vessel deformation 15 min after start of strip like cooling

CONCLUSIONS

The emergency core cooling system injection in case of primary or secondary blow-down effects one of the main load cases to be analyzed in the integrity assessment of reactor pressure vessels. The interacting parameters of fracture mechanics analyses are the load pattern, the material properties and the postulated cracks. Large scale thermal shock experiments analysed by pre- and postcalculations as well as parametric studies to investigate the influence of dominant factors show that in case of axisymmetric loading high stresses appear only near the cooled surface in the first minutes of the transients. In contrary axial strip like cooling effects a stretching of the cooled regions characterized by an increasing stress intensity over the ligament for some time predominantly for circumferential cracks.

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