

Pressurized Thermal Shock Loading of HDR RPV-Nozzle and Cylindric Wall

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1 Introduction

In the case of an accident connected with loss of coolant, sufficient cooling of the reactor core is taken care of by the afterheat removal system. The relatively cold medium causes thermal shock loading to the inlet nozzle and the cylinder wall below it. In the course of this loading steep temperature gradients are built up over the wall which bring about high stress and strain concentrations. In the HDR-Safety Program loadings of this type on the reactor pressure vessel were repeated under extreme conditions until crack initiation and cyclic crack growth appeared /1/. The cylinder wall and a nozzle were subjected to comparatively realistic thermal shock loadings over comparatively long periods of time, and these are examined in the present document.

2 Problem Solving Method

The thermal shock tests carried out for the purposes of this investigation on the pressure vessel of the HDR (whose most important measurements are set out in Figure 1), in each case at a system pressure of 106 bar and system temperature of 305 °C, involved the following stages:

- Temperature stratification tests in the vessel when crack-free,
- Cyclic loading with short thermal shocks and high temperature difference of 280 K in order to produce natural cracking (thermal fatigue),
- Long term thermal shock loading with various temperature differences

temperature development across the cylinder wall in cross-sectional alignment to the crack at selected times. The calculated development of the J-integral over the testing period as a result of this temperature distribution and the prevailing internal pressure is shown in Figure 4. In contrast to the rotationally symmetric analysis in Figure 2, the J-integral does not attain a maximum value, but continues to increase monotonically throughout the duration of the test /4/.

3.2 Loading of the Nozzle Edge Crack

The crack fields which had developed particularly in the lower area of the nozzle A2 are characteristic of crack development under conditions of thermal fatigue where no initial notch has been introduced. In order to satisfy the demands of non-destructive examination, a wrap-around substitute crack in 180° alignment was included in the calculation, Figure 5. The calculated temperatures and COD values correspond relatively well with the measured values. The development of the J-integral with time is basically different from that which occurs in the cylinder wall with strip cooling. Generally speaking, the value of the J-integral increases, and after only approx. 120 s reaches a definite maximum, whereby the position in the immediate vicinity of the nozzle edge displays the highest J values and consequently is subjected to the highest loading, Figure 4 /4/. This development corresponds qualitatively with that in the cylinder wall in the case of a rotationally symmetric configuration, Figure 2.

4 Evaluation of the Loading

Assessment of the performance of the component is carried out in connection with the corresponding material parameters. A statement with regard to crack growth is possible with crack initiation parameters /5/. The scatter band of the J values in Figure 4 shows that stable crack propagation is probable. After the test the crack regions were removed for fractographic analysis. Comparison of the fracture surface with the contour which forms the basis of the calculation in keeping with non-destructive examination data, shows that the actual size of the crack was significantly smaller. Indications of stable crack propagation could not be determined. In other words, the significantly smaller crack depth meant that the loading at the crack tip was less, and the initiation values were apparently not attained.

between 70 and 225 K for the examination of stable crack growth. The following section gives information on the long term thermal shock tests carried out on the cracked cylinder wall and the cracked nozzle corner.

3 Analysis of the Long Term Thermal Shock

The simplest calculation method for approximate determination of the crack loading assumes a rotationally symmetric condition both for the loading (rotationally symmetric cooling) and for the crack geometry (perimeter crack over the whole perimeter). The analysis of the crack in the cylinder wall was carried out with the Finite Elements (FE) Program OCA /2/ developed for these conditions, which only allows linear elastic calculations. The development of the stress intensity factors for three depths of crack, calculated for a cooling cycle of 60 min. where $T = 280$ K (temperature reduction from 305 °C to 25 °C), are represented in Figure 2 as a function of time. In the process of this development maximum loading is attained after approx. 2 min., and as is to be expected this increases according to the depth of crack. However, the most unfavourable loading conditions of the RPV must assume asymmetric strip cooling of the wall and a limited crack length. For the tests on the pressure vessel, therefore, an arrangement was conceived whereby both the cylinder wall and the nozzle can be cooled simultaneously. Accordingly, cooling of the cylinder wall was carried out in lamellar fashion and that of the nozzle rotation symmetrically. The cracks in the nozzle were oriented longitudinally, those in the cylinder wall circumferentially. The cooling water is guided through a 10 mm wide annular downcomer for a length of 300 mm through the nozzle A2 into the RPV. There, it flows in a 500 mm wide and approx. 3000 mm long guide channel vertically downwards along the wall of the RPV to the nozzle F, see Figure 1.

3.1 Loading of the Cylinder Wall Crack

A semi-elliptical surface notch introduced mechanically served as the initial notch for the thermal fatigue crack. More precise advance calculation of the actual conditions at the crack front was achieved by means of the Finite Element Method, with the program system SMART and PERMAS /3/. The complex problem was idealized and calculated three dimensionally, and elastic-plastic material behaviour was also taken into consideration. In keeping with non-destructive examination data, the prediction was based upon a semi-elliptic surface crack with a length of 62 mm and depth of 28 mm. Figure 3 shows

5 Summary

Cracks were introduced on a nozzle and on the cylinder wall from notches and on the smooth surface of the wall by means of cyclic thermal shock loading with temperature differences of 280 K. These cracks were subjected to long term thermal shock loading of varying intensity and at maximum system pressure. Rotationally symmetric cooling of the nozzle and strip cooling of the cylinder wall were chosen as these cause the greatest loading. Three dimensional elastic plastic Finite Elements Analysis gives relatively good correspondence with the measured temperature and COD values. Fracture mechanical assessment allows us to assume stable crack propagation which could not be established on the fracture surface. This results from the fact that the crack depth on which the calculation was based was significantly larger than the actual crack depth.

References:

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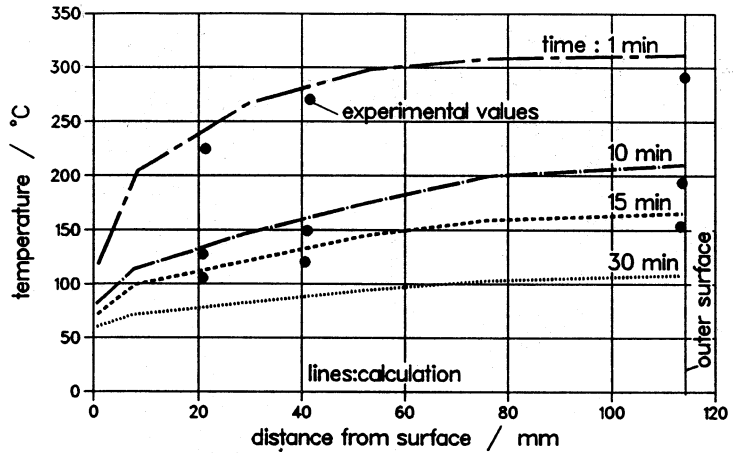


Fig. 3: Comparison of calculated and measured temperatures in the RPV-wall during thermal shock

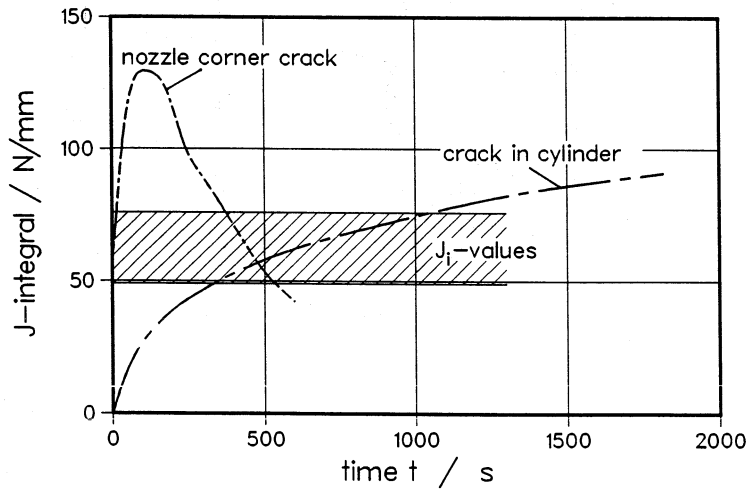


Fig. 4: Calculated J-integral values of nozzle corner crack and crack in cylinder wall

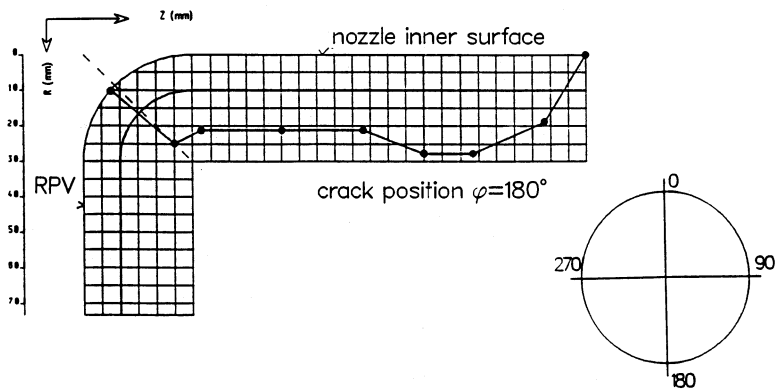


Fig. 5: Assumed crack shape in the nozzle according to non-destructive testing results

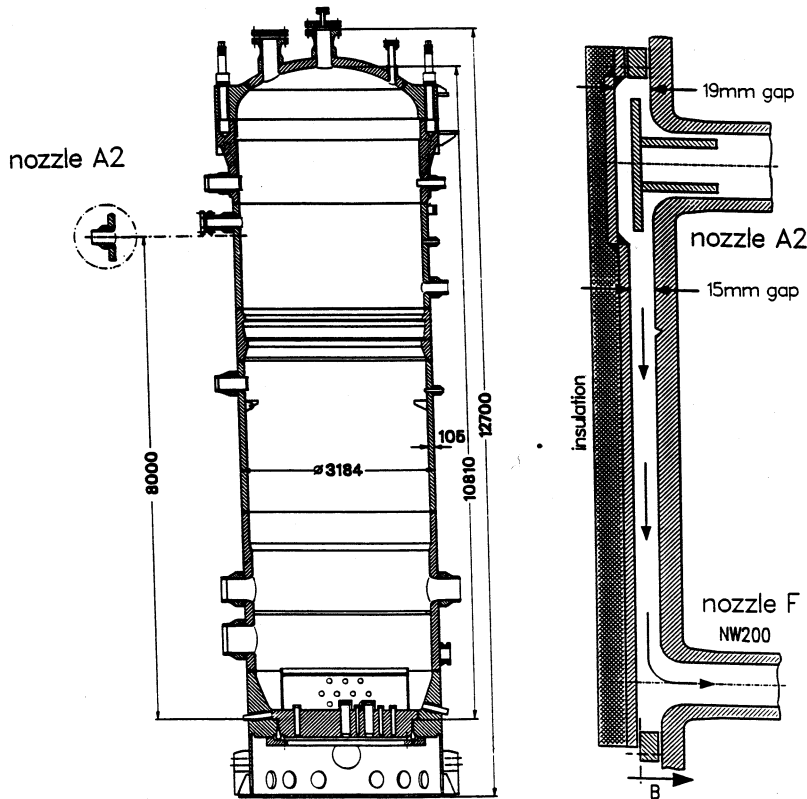


Fig. 1: HDR-reactor pressure vessel and cooling device

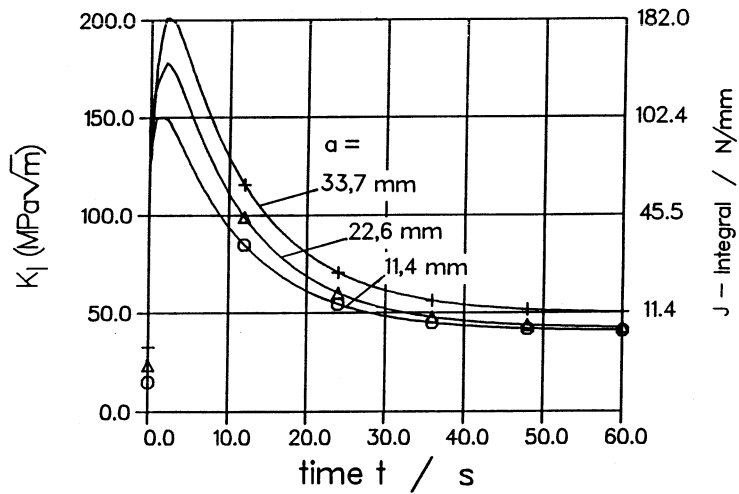


Fig. 2: K_I resp. J-integral for a circumferential crack in the cylinder-wall subjected to axisymmetric cooling