Crack Initiation and Crack Propagation at the Cylinder Wall of HDR-Pressure Vessel under Cyclic and Pressurized Thermal Shock Loading

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INTRODUCTION

In case of an incident in conjunction with a loss of coolant, the heat removal system provides for sufficient cooling of the core of the reactor. This relatively cold medium generates a thermal shock in the inlet nozzle and the cylinder wall below. At this load, steep temperature gradients are built up over the wall, which generate high strain and stress concentrations. In the HDR safety program, these types of loads were frequently repeated in order to register the crack initiation phase and the crack propagation quantitatively and in order to be able to compare them to calculation models. This primarily was the objective of the investigation of the thermal shock tests on the cylinder wall below the nozzle A2.

APPROACH

The thermal shock investigations performed to this end on the pressure vessel of the HDR whose most important dimensions are summarized in Figure 1, included the following examinations:

- cyclic thermal shock tests on the cylinder wall with brief thermal shocks to produce cracks

- long-term thermal shock tests on the cylinder wall on pressure vessel areas with incipient cracks.

The object of these investigations was the edge of the nozzle A2 of the RPV and a section of the cylinder wall which was subjected by repeated thermal shocks. With a temperature difference in the individual cycle of some 260 °C within 10 seconds, the transient was selected in such a way that it covers with a high degree of reliability all possible operating and incident loadings. The water in the reactor pressure vessel (310 °C, 106 bar) was enriched in phases by 8 ppm of oxygen, in order to cover the corrosive effect of the medium under cyclic loads to ensure the utmost in safety.

Following this, the cylinder wall of the reactor pressure vessel with incipient cracks was now subjected to an extended thermal shock (long-term thermal shock). Initially, the cooling was performed by a natural injection of the cold water into the RPV as close to reality as possible followed by a guided cold water jet which was introduced in the nozzle area rotation-symmetrically, constituting the most unfavorable condition.

RESULTS OF THE INVESTIGATIONS

1. Cyclic thermal shocks

In order to perform the tests on the cylinder wall with limited efforts, the relevant point was to be sealed in a box from the medium of the RPV. The thermal load was applied by a special water-circuit, which produced temperature differences between 260 and 280 °C. The optimization of the cooling surface relative to a maximum load was performed with the aid of a linear-elastic finite element analysis. This resulted in a maximum load for a cooling width of 2 x 10° angle at circumference /1/.

The investigation showed that a strip-type thermal shock, a circumferential crack is subjected to stress to a much higher degree than a longitudinal crack, in which case the load caused by the inside pressure can be neglected. On the basis of these results, a width of the cooling of 500 mm was chosen. This corresponds to an angle at circumference of approx. 19°.

With the aid of a three dimensional FE calculation, the height of the cooling box was fixed to be 400 mm /2/; for the test setup see Figure 2. On the basis of these dimensions, there are areas in the cooling surface in which the circumferential stress as well as the axial stress is dominant. This allows the investigation of crack initiation in the circumferential and axial direction.

In view of the following long-term thermal shock investigations, a 1 mm deep notch was carved in the direction of the circumference as a crack initiator on the basis of the calculation results /1/ at the start of the test series. After 3000 temperature cycles, it appeared that no crack initiations were visible on the smooth surface and that only a minimal crack had been generated in the base of the notch. In order to shorten the test times, two additional notches which were 5 mm and 10 mm deep were carved. After an additional 6500 temperature cycles, the test series was ended since, according to the information of the non-destructive tests, a crack of a depth of approx. 30 mm had been developed at the deepest notch /3/.

A fracture-mechanical analysis of the condition now achieved was to show under which marginal load conditions a maximum crack propagation was to be expected with a view to the long-term thermal shock. In addition, the size of the crack was to be determined at which the initiation value was reached and a stable crack growth occurs additionally. Further, attempts were made to verify the experimental finding with theoretical methods.

The simplest calculation method is the assumption of a rotation-symmetrical condition for the temperature load (rotation-symmetrical cooling) as well as for the crack geometry (circumferential crack over the entire circumference). The analysis was performed with the finite element program OCA /4/ developed for these conditions which allows only a linear-elastic calculation. The progressions of the stress intensity factors calculated for a cooling cycle of 60 minutes with ΔT = 280 °C (cooling from 305 °C to 25 °C) for three crack depths are shown in Figure 3 as a function of time /5/. In such a case, the maximum stress intensity factor is reached after approx. 2 minutes which increases as expected as the depth of the crack increases.
For a comparision, a much more complicated three dimensional elastoplastic FE calculation with the three crack geometries as shown in Figure 4 was performed /6/ with the same marginal conditions. In contrast to the simple OCA analysis, the J-integral values increase with time in the entire time interval investigated, in which case the increase of the J-integral of the 50 mm deep crack are far greater than for the crack of the depth of 20 mm, Figure 5. In this connection, it must be noted that the linear-elastic calculation considerably underestimate the J-integral for time t = 600 s, i.e. is not on the safe side, Figure 3 and 5.

If one enters the maximum possible scatter band of the J-integral values into Figure 5, the 20 mm deep crack could initiate with long-term cooling. For these conditions, the 50 mm deep crack, however, would show a stable crack growth in any case. Subsequent to these tests, the size of the crack geometries were registered as accurately as possible using NDE methods, Figure 6 and to this end an elastoplastic FE analysis was performed in order to specify the test conditions for the long-term thermal shock tests.

2. Investigations on the long-term thermal shock

Since the tests relative to the long-term thermal shock were to cover the cylinder wall as well as the area of the nozzle A2, a device was designed by which both areas could be cooled at the same time. This was achieved with the cooling device shown in Figure 7, in which case the cooling of the cylinder wall was now strip-type.

The cooling water is conducted through a 10 mm wide circular gap on a length of 300 mm through the nozzle A2 into the RPV. There, it flows into a 500 mm wide and approx. 3000 mm long guide box along the RPV wall vertically down to the nozzle F.

To this end, a precalculation was done applying the finite element program SMART and PERMAS in order to determine the time-dependent temperature fields, stress distributions and the J-integral values as a result of the thermal shocks in three dimensional geometric configurations /7/. The crack contour on which the calculation is based is shown in Figure 6.

With due allowance for the conditions of symmetry, the discretisation shown in Figure 8 resulted.

The calculation procedure was as follows:

- transient temperature field
  thermal starting condition T = 305 °C
  heattransmission value constant 5000 $W/(m^2\,°C)$
  coolant temperature 50 °C

- elastoplastic stress analysis
  the elastoplastic analysis was based on the temperature field calculation
  temperature dependent flow curves ($\sigma = f(\varepsilon, T)$)
  starting conditions for calculation 50 °C; 1 bar
  internal pressure elastoplastic forecast at 106 bar and 305 °C
  the structure was assumed stress free at 50 °C

The comparison with the measured temperature shows a relatively good agreement with the calculated results.

The crack mouth opening CMOD calculated elastoplastically, however, is higher than the one determined from the measurement, Figure 9.

After the end of the test, a bore core was taken in the area of the deepest crack and the crack surface was uncovered. In doing so, it showed that the depth of the crack determined with the non-destructive tests prior to the long-term shock test had been highly overestimated. Figure 10 shows the actual crack front as compared to the one measured with the non-destructive methods and used in the calculation. In addition, the crack front determined at the end of the test in the laboratory using the NDE methods on the basis of two different cladding thicknesses are entered in this figure. Here the agreement with the actual size of the crack is much better.

Indications of stable crack growth on the crack surface were not found.

With fractographical and metallographical investigations crack branchings were found, Figure 11. These crack branchings were generated during the cyclic thermal shock periods in which partly an oxygen content of 8 ppm was prevalent. Similar cracks occurred during the cyclic tests on a vessel of intermediate size (ZB1). This vessel, however, was only subjected to pulsating interior pressure at constant temperature /8/.

Since the calculation is based on the deeper crack front measured on the basis of the NDE method before the long-term thermal shock, this makes it understandable that the calculated crack mouth opening CMOD, Figure 9, displays higher values.

SUMMARY

In the area of the cylinder wall, cracks were produced by cyclic thermal shock loads with temperature differences from ΔT = 280 °C in the base of the notches and on the smooth wall. These cracks were subjected to a single long-term thermal shock with ΔT = 280 °C and with full pressure of p = 106 bar. A strip-type cooling of the cylinder wall, which provides the highest stresses, was selected.

The precalculations of the stresses at the deepest crack in the cylinder wall was based on the crack front measured before the test with the NDE method which greatly overestimated the depth of the crack as shown by the fractographic investigation. As a result, the calculation showed excessive crack mouth opening displacements.

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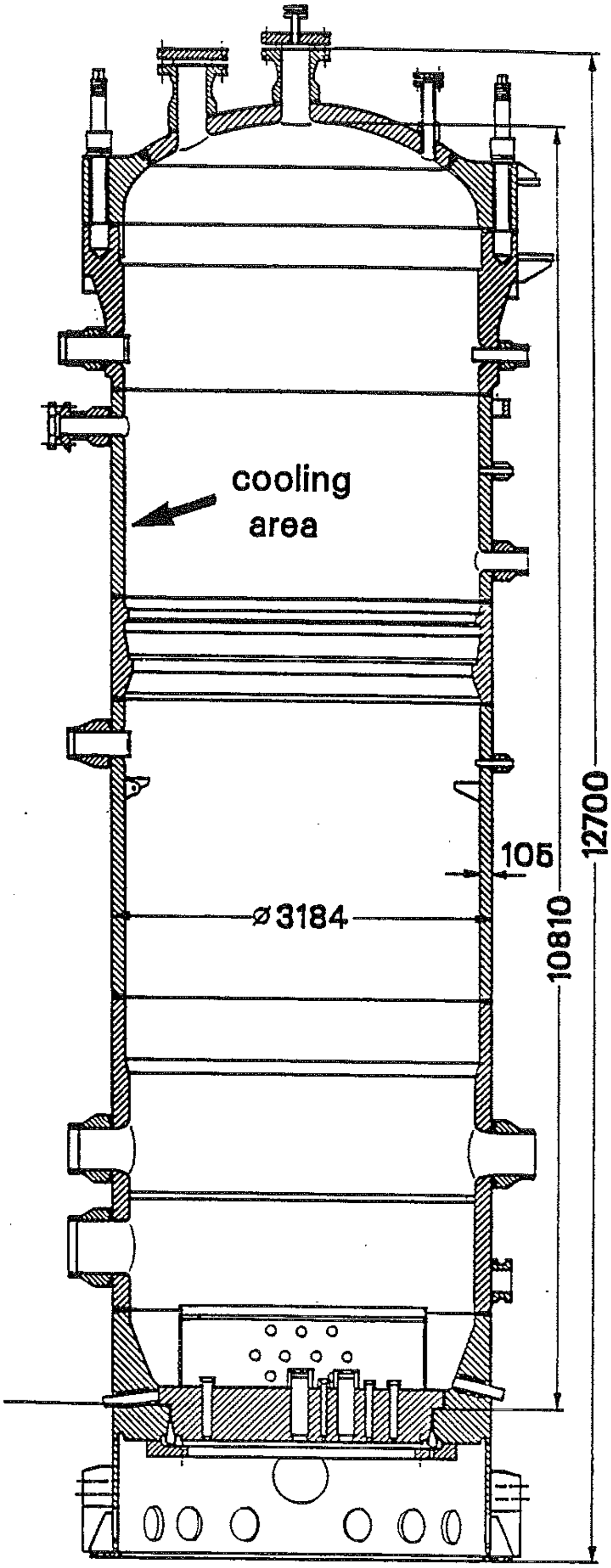

Fig. 1: HDR- pressure vessel
(dimensions in mm)

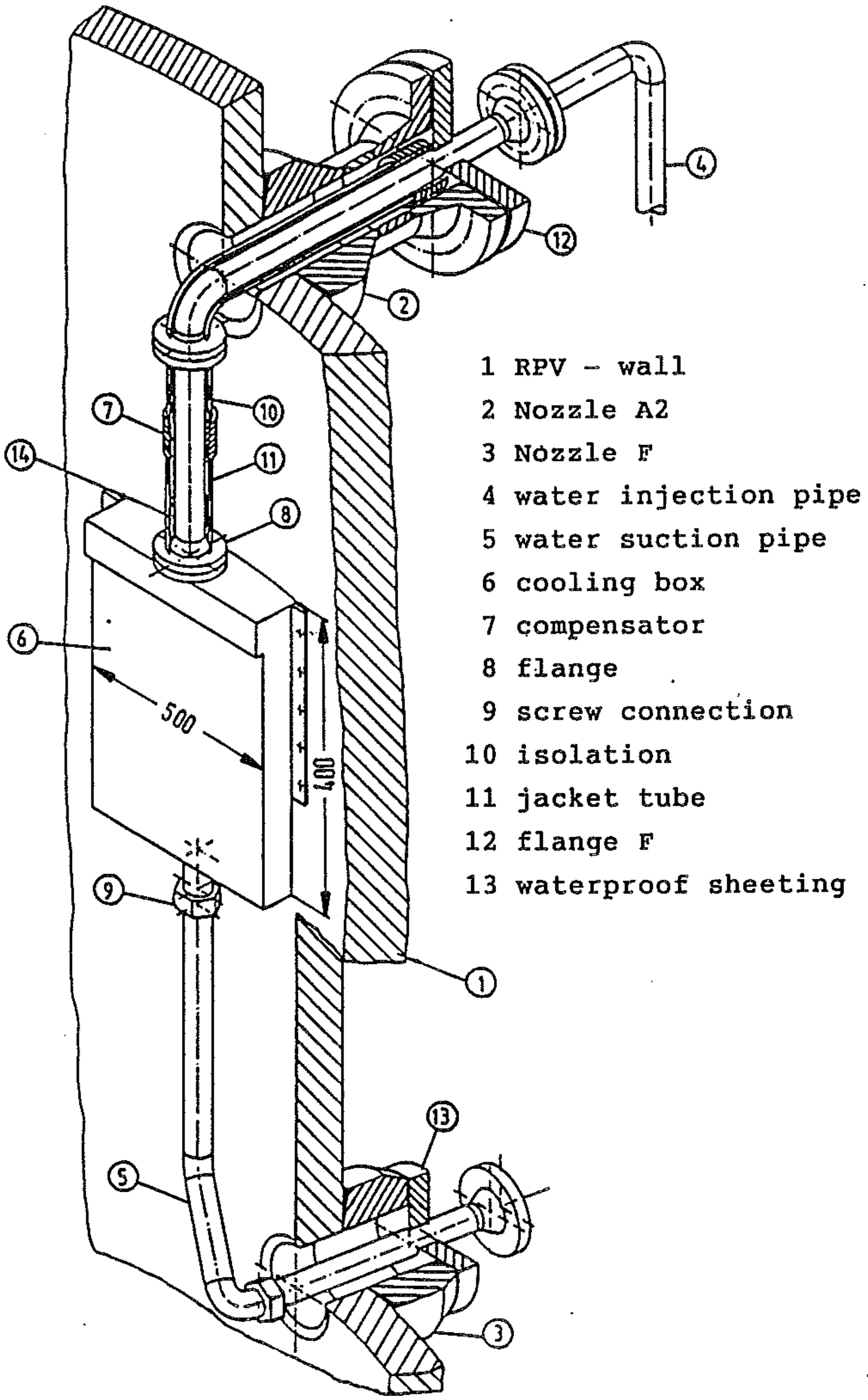

Fig. 2: Experimental arrangement for the cyclic thermal shock loading

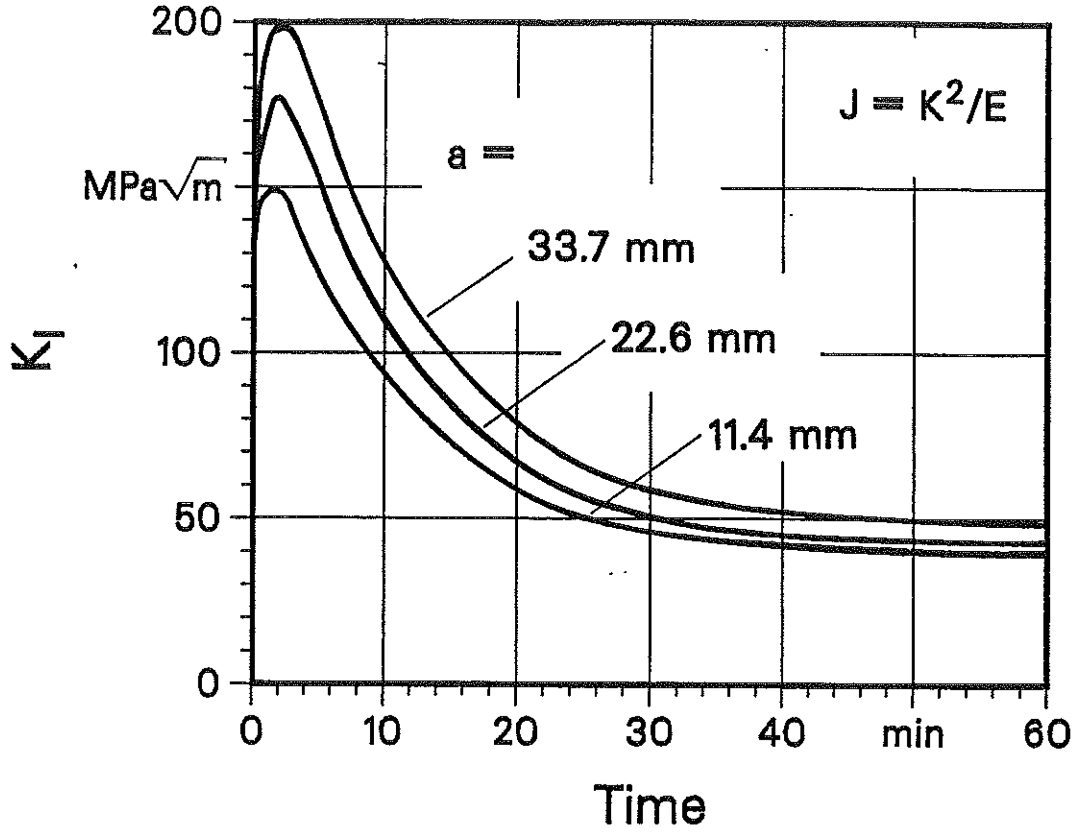

Fig. 3: K_I (J-Integral) for a circumferential crack in the cylinder wall under axisymmetric cooling

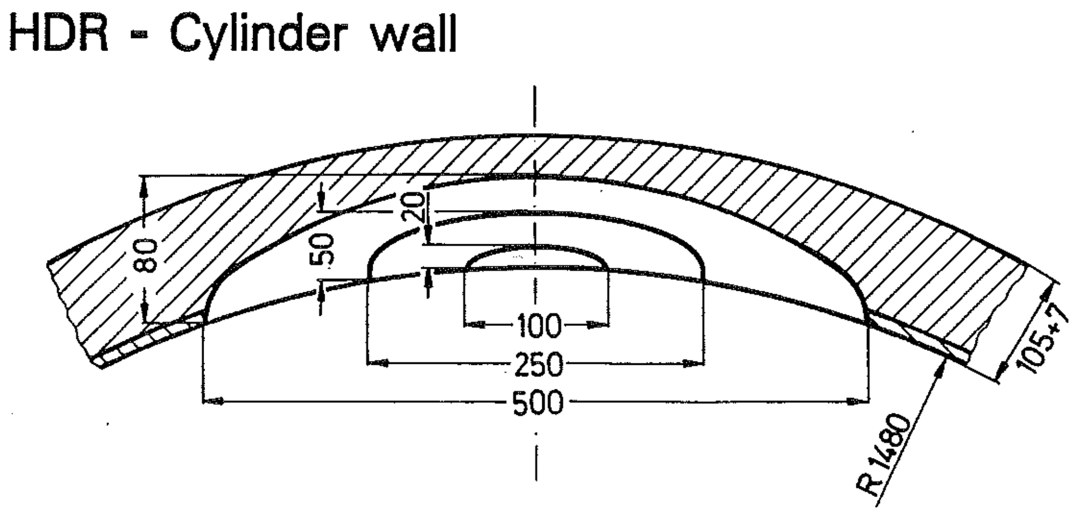

Fig. 4: Crack assumption for the FE-analysis (cyclic thermal shock loading; cooling box)

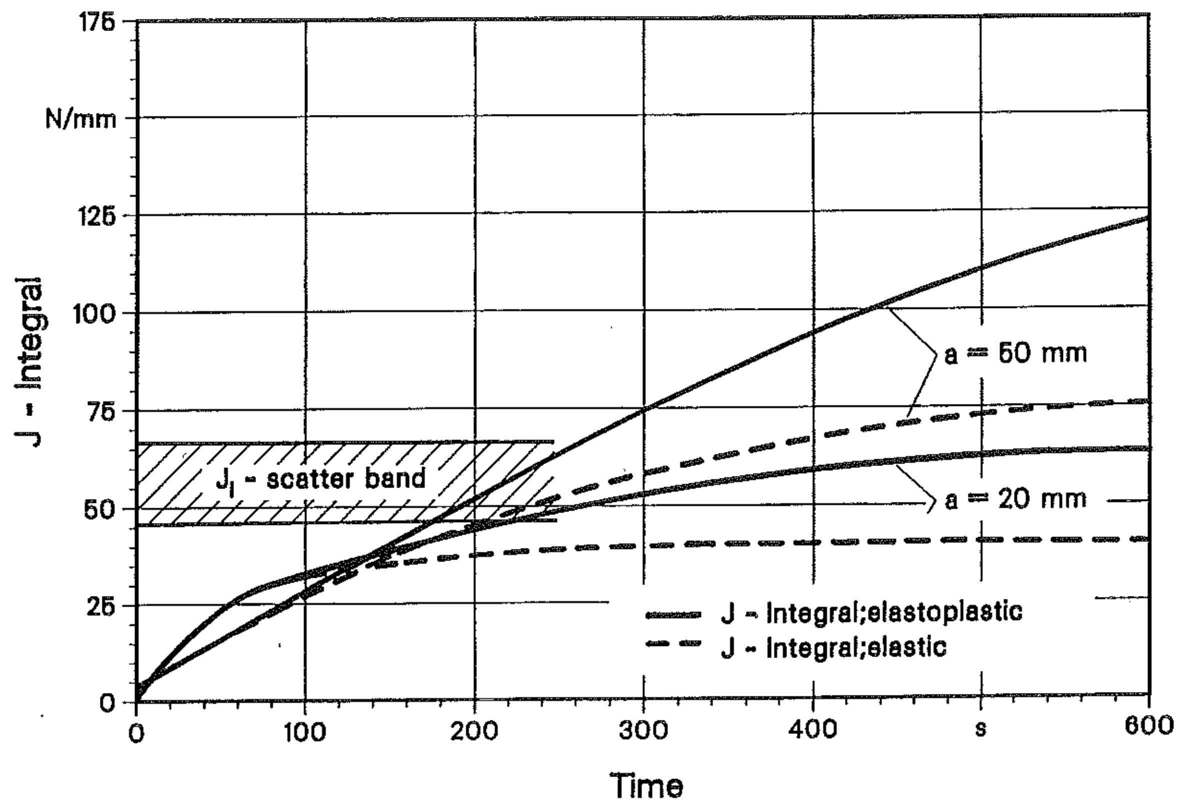

Fig. 5: J-Integral on the base of the cracks.

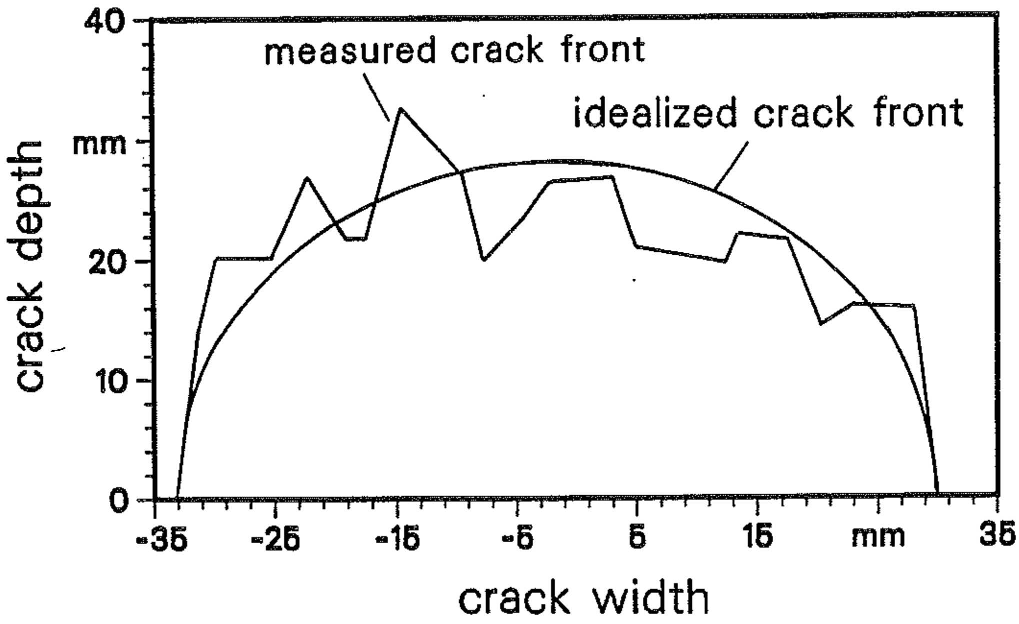

Fig. 6: Used crack front for the FE-calculation
(long-term thermal shock; strip cooling)

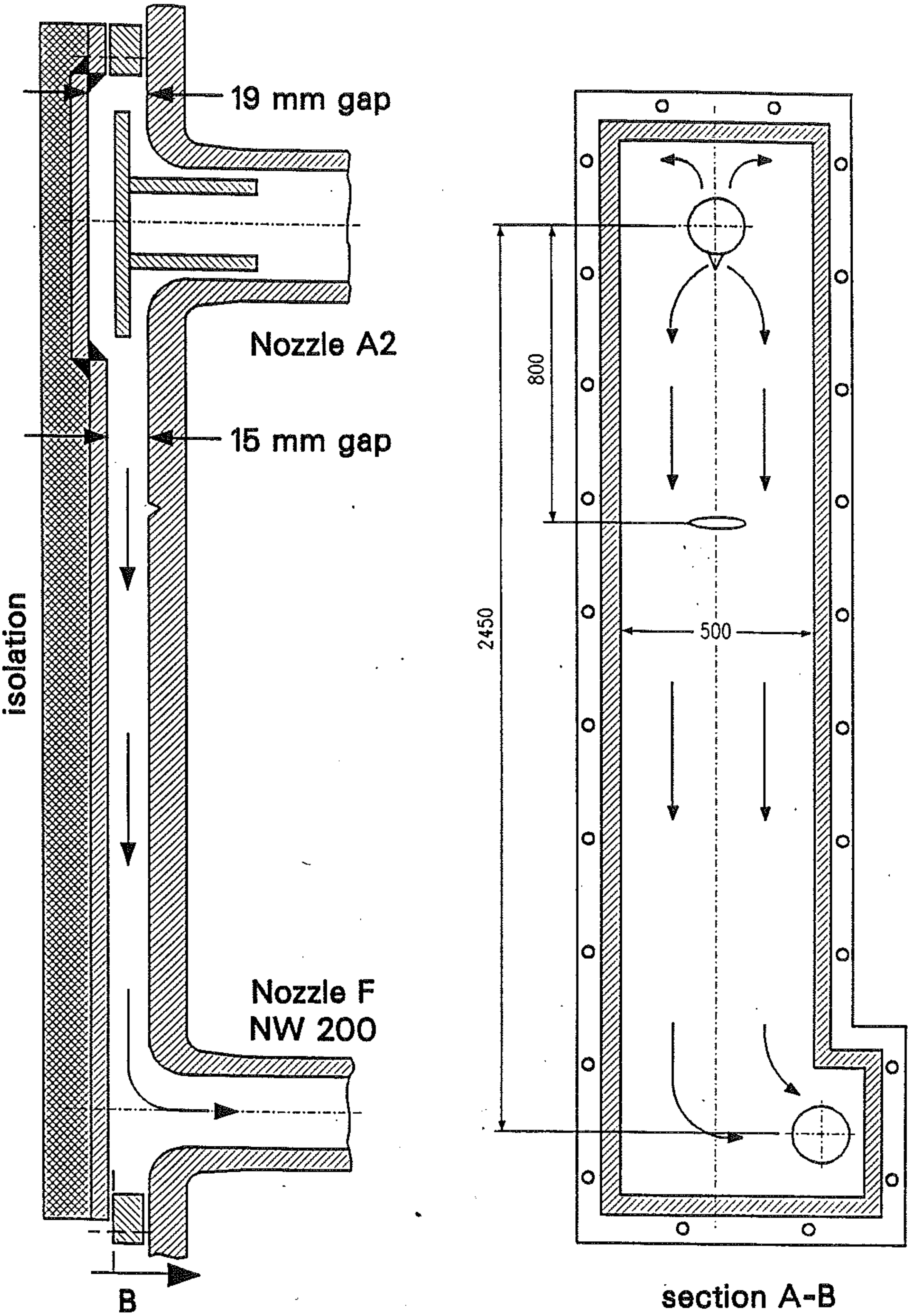

Fig. 7: Test arrangement for the strip cooling

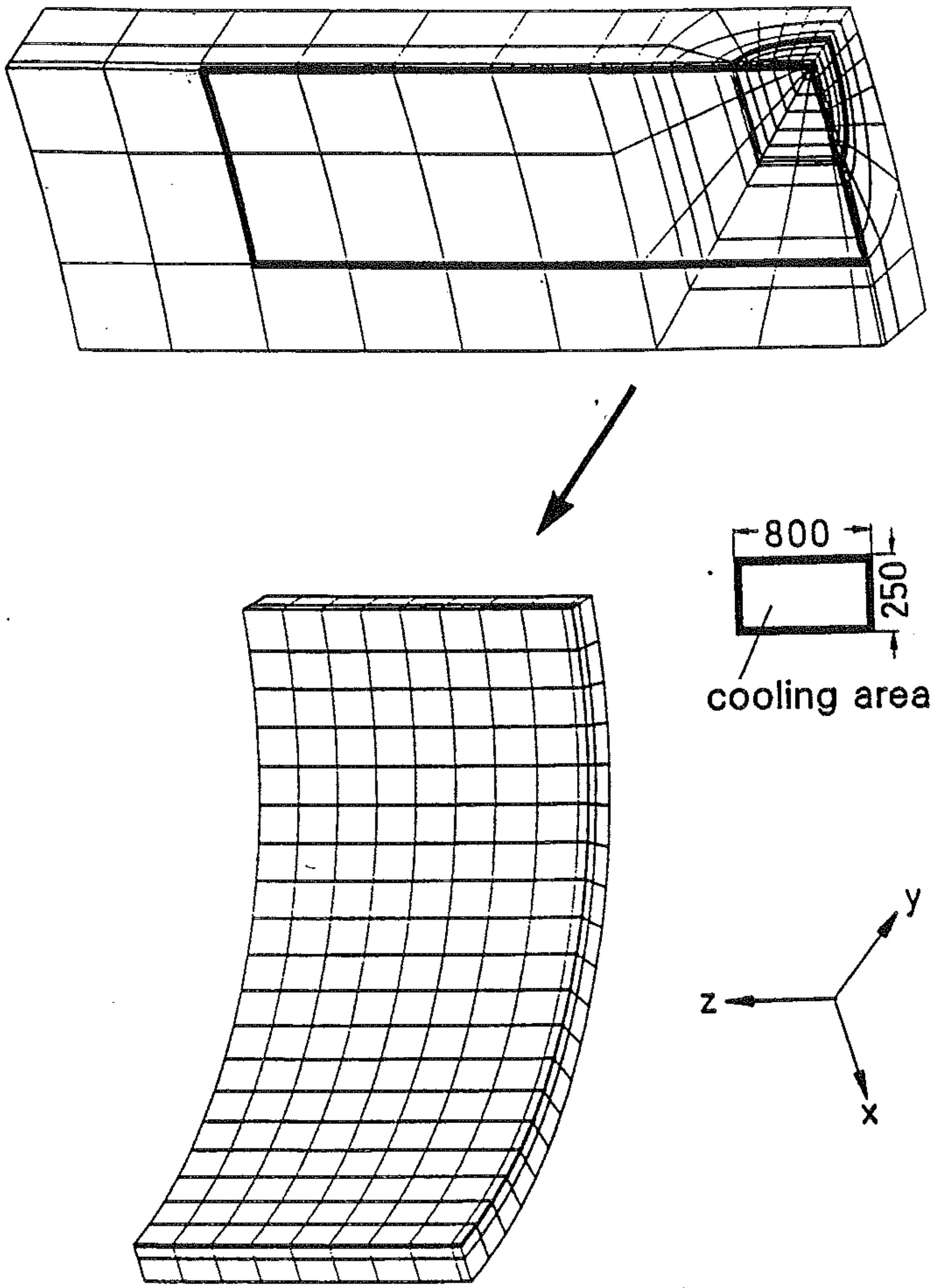

Fig. 8: Idealisation of the cylindric wall

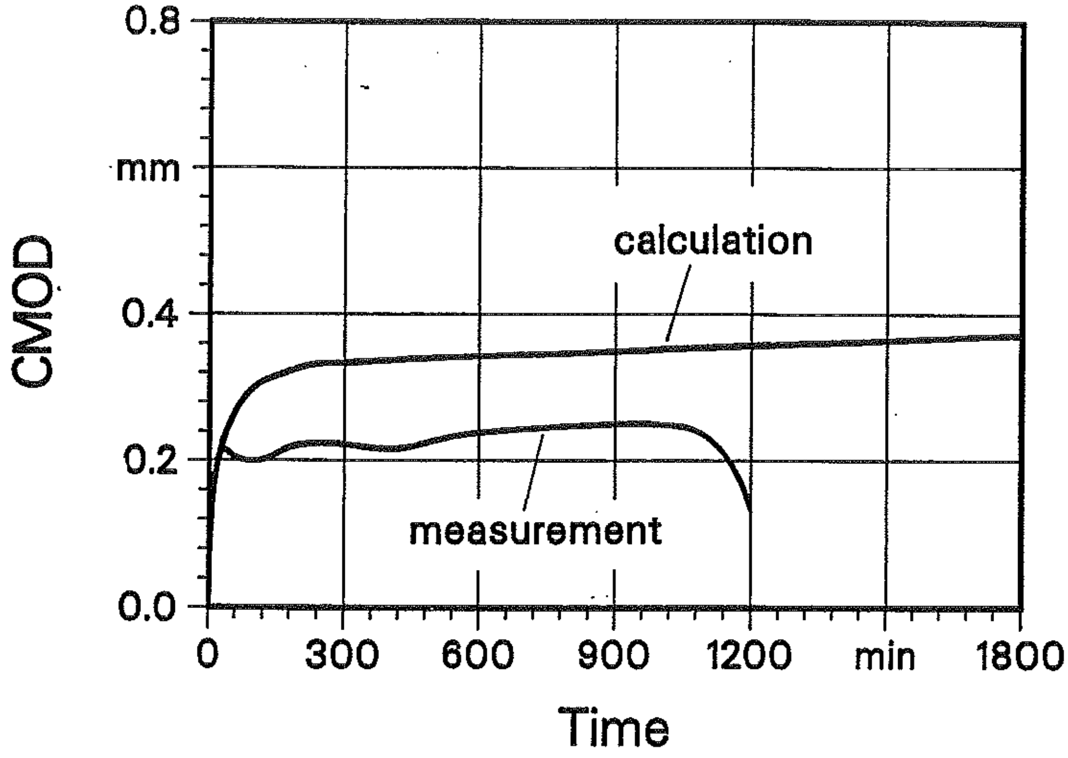

Fig. 9: Measured and calculated crack mouth opening displacement CMOD (long-term thermal shock)

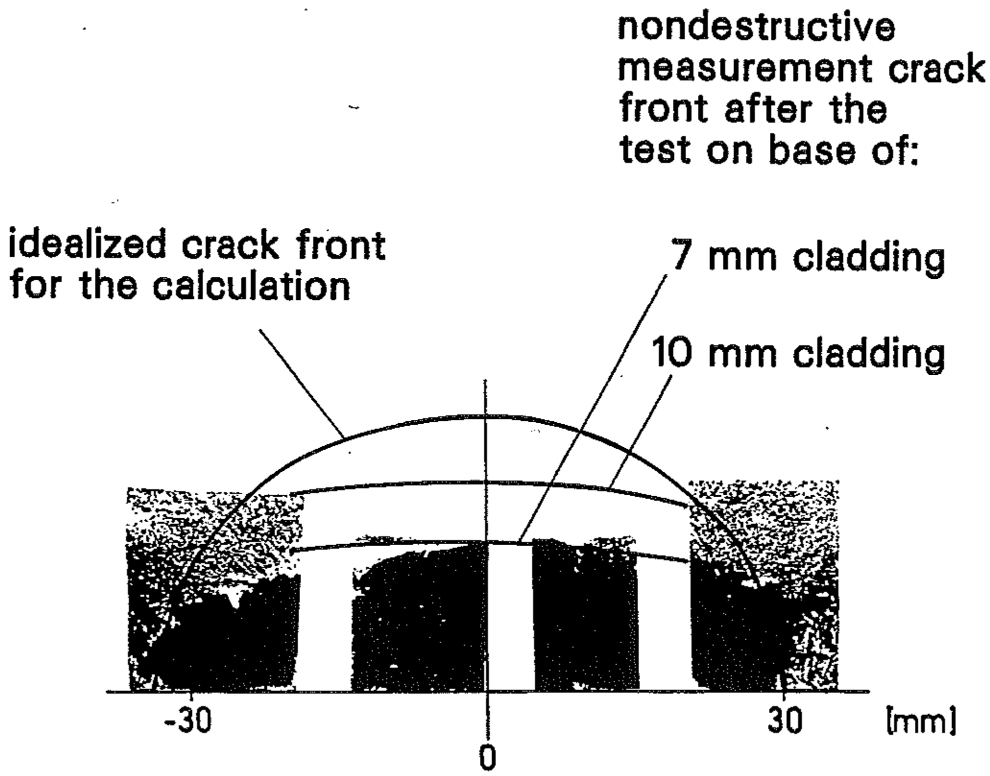

Fig. 10: Comparison of the real crack front with the assumed crack front for the calculation

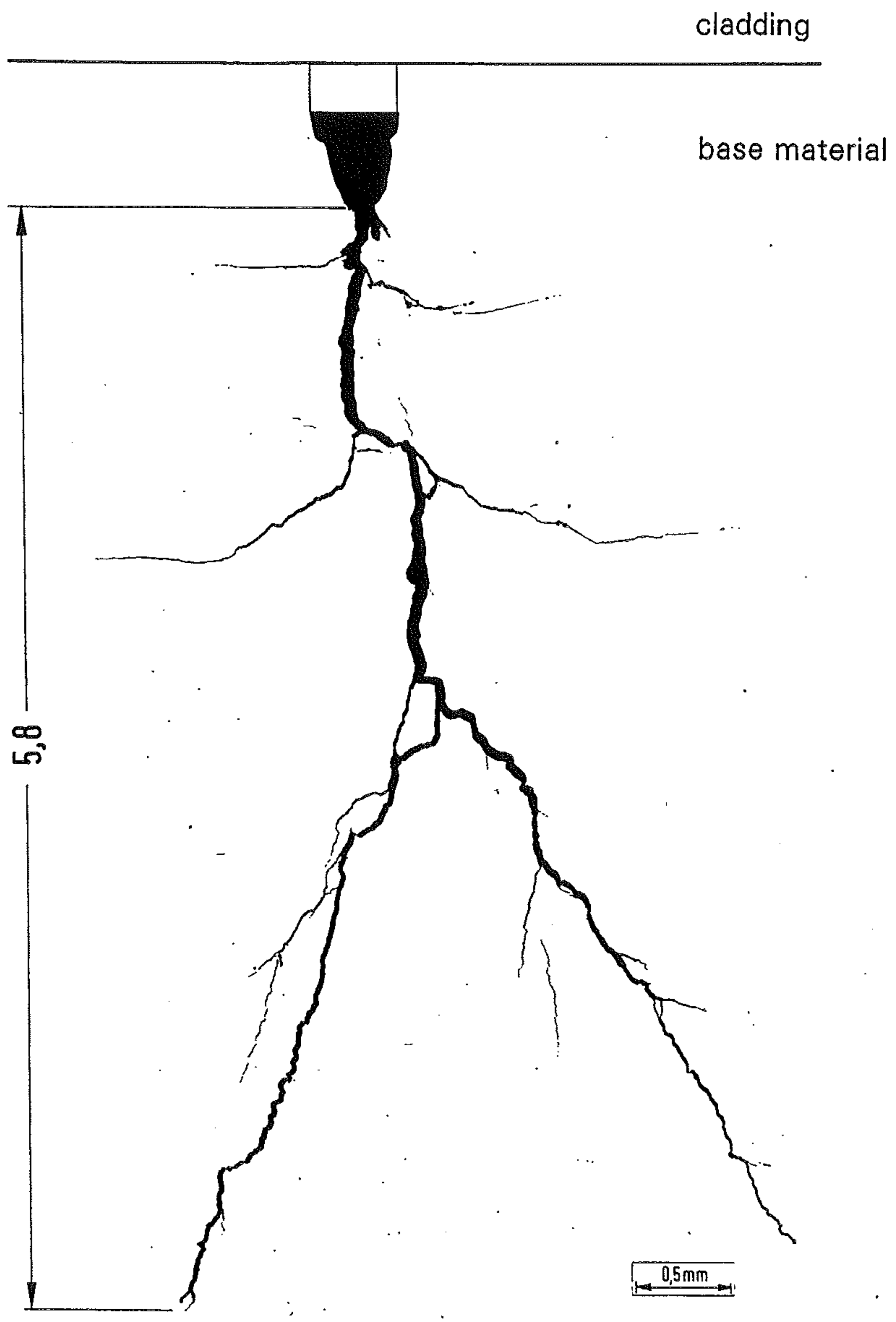

Fig. 11: Thermal shock crack in the cylinder wall of the HDR RPV