Investigation of the leakage behaviour of reinforced concrete walls

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1 Introduction

Information about the leakage behaviour of the containment in case of an accident is of decisive importance for the verification of nuclear power plant safety. Assuming a core melt accident with failure of the reactor vessel in a pressurized water reactor, high internal pressures accompanied by temperatures well over the water boiling temperature can occur. During loss of the primary coolant a large quantity of steam develops. In case of resulting cracks through the entire thickness of a pre-stressed containment wall without liner an air-steam mixture enriched with aerosols may be released.

Regarding the leakage of pure air through cracked concrete walls there are a couple of investigations introducing correlations based on crack width and pressure differential, like [7], [12] for instance. The leakage behaviour of water through cracked concrete walls has already been investigated as well [3], [9]. Investigations on the leakage of steam and air through narrow, idealized cracks were performed in [1]. However, corresponding knowledge about the leakage of air-steam mixtures through real cracks was missing world-wide so far.

2 Conception of the experiments

The leakage observation can be divided in mechanical processes determining cracks through the wall and the thermo-hydraulic processes. The development of crack patterns and average crack widths can be calculated quite well using available numerical procedures like the finite element method [5]. Contrary to the mechanical processes it's difficult to describe the parameters governing the thermo-hydraulic processes inside the cracks like roughness, temperature, heat transfer and condensation.

Aim of the project was to analyse the thermo-hydraulic process of water-air leakage with condensation through known crack patterns. In contrast to other investigations on large scale model containments like MAEVA [8], it was not intended to simulate the integral behaviour of the containment as a whole but of a representative section of the containment wall.

Integral tests were performed on specially developed specimens with complex and realistic crack patterns. Due to the applied axial load during cracking the induced cracks are of almost uniform mean widths. The thermo-hydraulic load used for the tests followed a severe accidental scenario based on the design scenario for a core melting accident of the EPR (Fig. 1).

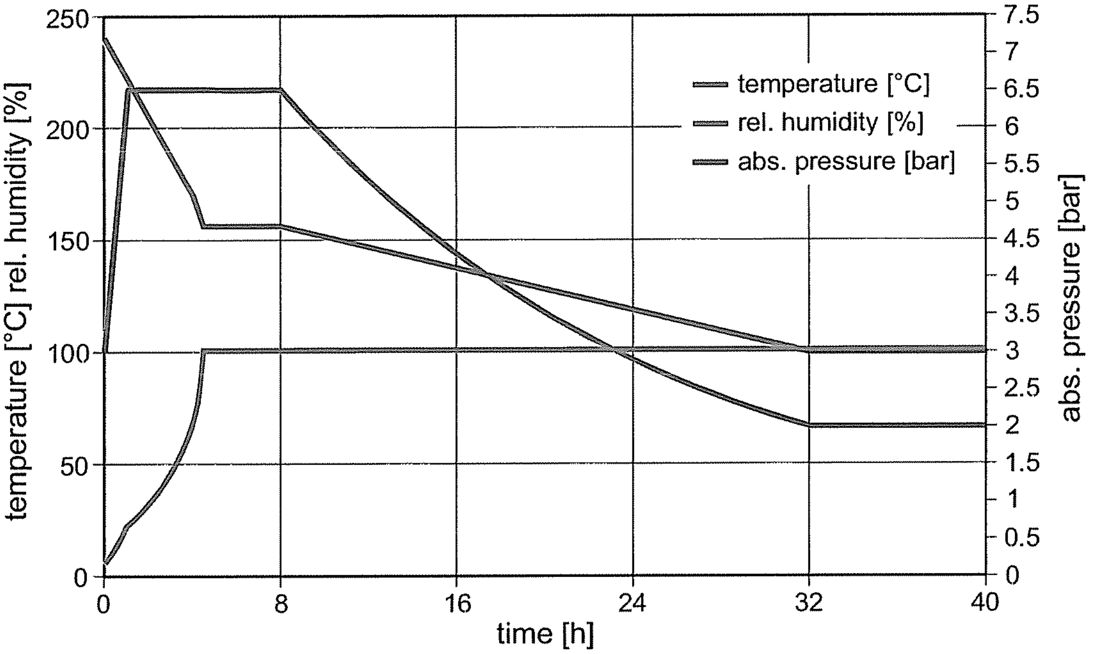

Fig. 1: Test scenario

3 Testing facility

3.1 Mechanical set-up

The mechanical part of the testing facility consists of a load frame, two abutments, 12 hydraulic jacks, a pressure chamber above the specimen and a control room underneath. The mechanical set-up is shown in Fig. 2 and Fig. 3. The abutment for the anchorage and the abutment for the hydraulic jacks are connected together with the load frame and form a closed load path between the jacks and the abutments.

Additionally the load frame holds down the reinforced concrete cover of the pressure chamber and works as an abutment for pressure cushions sealing the cracks at the side of the specimen. Above the specimen is a steel made insulated pressure chamber, fixed by a reinforced concrete cover and bolted down to the load frame. The pressure chamber has an area of 3,28 m² and a volume of about 1 m³. The air-steam-mixture enters the pressure chamber at one side. After leaking through the specimen the outflow of condensed water and air is trapped in a control room. The amount of leakage is measured after the control room.

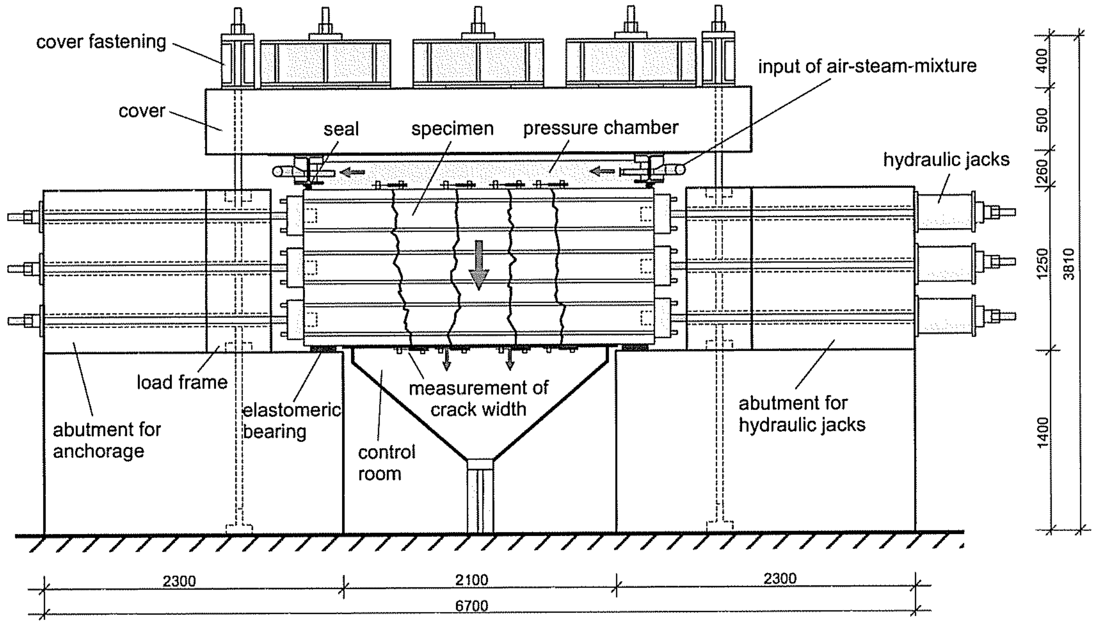

Fig. 2: Vertical cross section

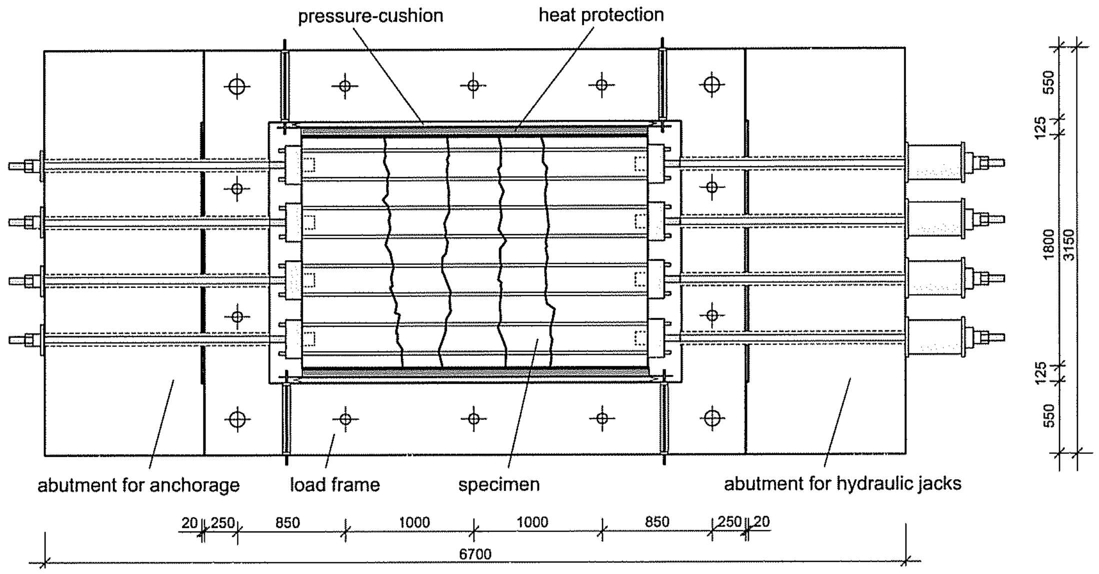

Fig. 3: Horizontal cross section

In order to ensure the desired pressure, temperature and humidity conditions and to avoid unwanted condensation, a minimum flow through the pressure chamber is established by opening an additional bypass valve opposite the mixture inlet.

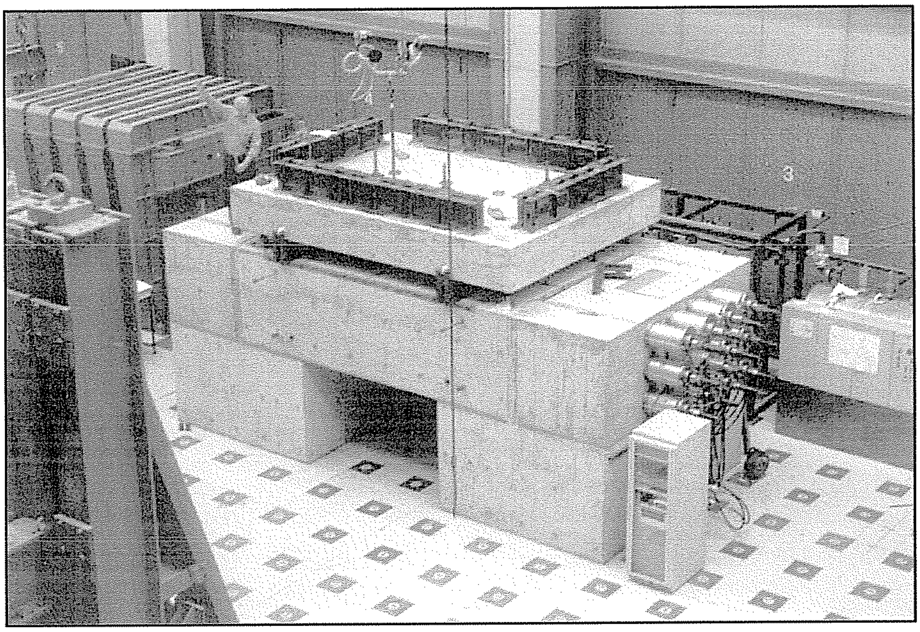

Fig. 4: Total view of the testing facility

3.2 Thermo-hydraulic set-up

Aim of the design process of the thermo-hydraulic set-up was to achieve stable air-steam mixtures matching complex, highly time dependent accidental scenarios. To fulfil the predefined accidental scenarios it is necessary to regulate the parameters temperature, partial pressure of steam and partial pressure of air. These three parameters describe the physical state completely at any time. The production principle of the air-steam-mixture is shown in Fig. 5. Unlike temperature, the parameters partial pressure air and partial pressure steam are not available for direct measurement. It is necessary to define the system state in equivalent measurable parameters. Instead of the partial pressures the total pressure and the relative humidity are measured and taken as control parameters.

The main parts of the air-steam mixture process are the compressor, boiler, static mixer, air heater, steam super-heater and 3 pneumatic valves.

The process can be divided in the air channel, the steam channel and the air-steam-mixture channel on the inlet side of the specimen, a bypass channel on the outlet side and the control room to collect leakage. The measurement and control system of the mixture production is realized using five control loops for temperature, pressure, relative humidity and minimum flow.

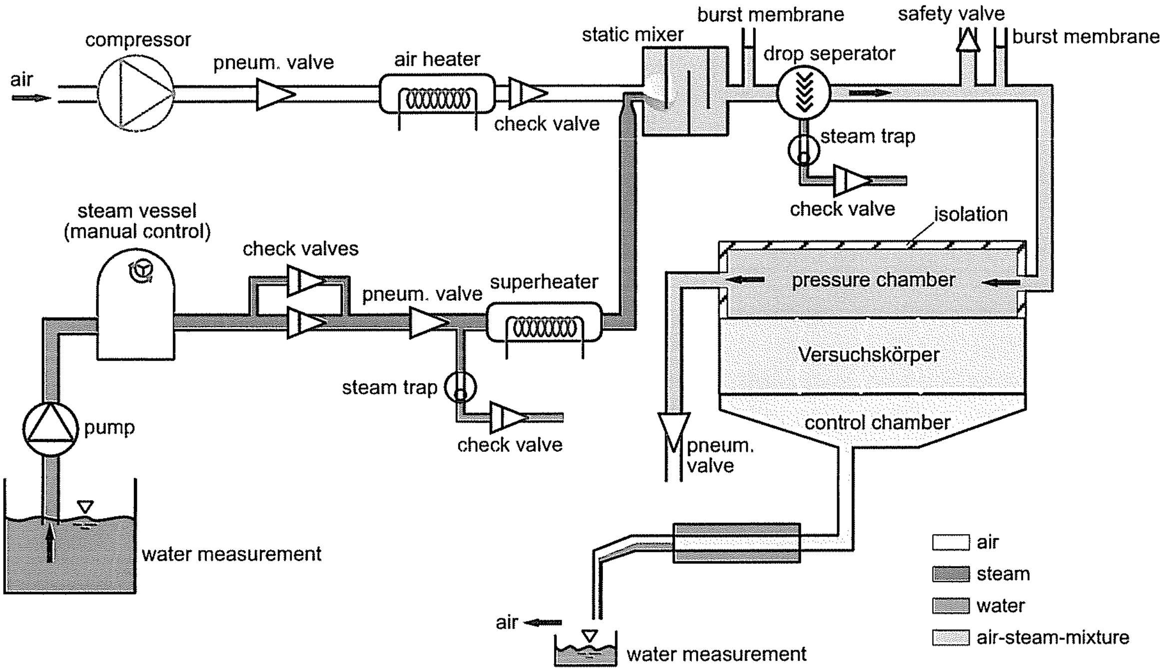

Fig. 5: Air-steam-mixture production principle

Temperature	100-162 °C	saturated steam-air mixtures
	100-250 °C	superheated steam-air mixtures
	20-250 °C	pure air
pressure	1-6,5 bar abs.	
relative humidity	1-100 %	
max. steam capacity	500 kg/h	
max. air capacity	150 kg/h	depending on compressor

Tab. 1: Capabilities of the air-steam-mixture process

3.3 Specimen

The specimen are reinforced concrete slabs with dimensions of 2,7 m x 1,8 m x 1,2 m. These dimensions are based on the following boundary conditions:

- Thickness of 1,2 m is equivalent to the design wall thickness of EPR
- The maximum force available for axial tensile cracking of the specimen limits the cross section area and determined the width to 1,8 m
- To achieve an observation area of 1,8 m x 2,0 m a total specimen length of 2,7 m is needed to allow load introduction being completed outside the observation area

Two different types of specimen with same overall dimensions have been developed. The first type has only longitudinal reinforcement. This allows a free development of the crack pattern along cross section. The reinforcement layout is shown in Fig. 6.

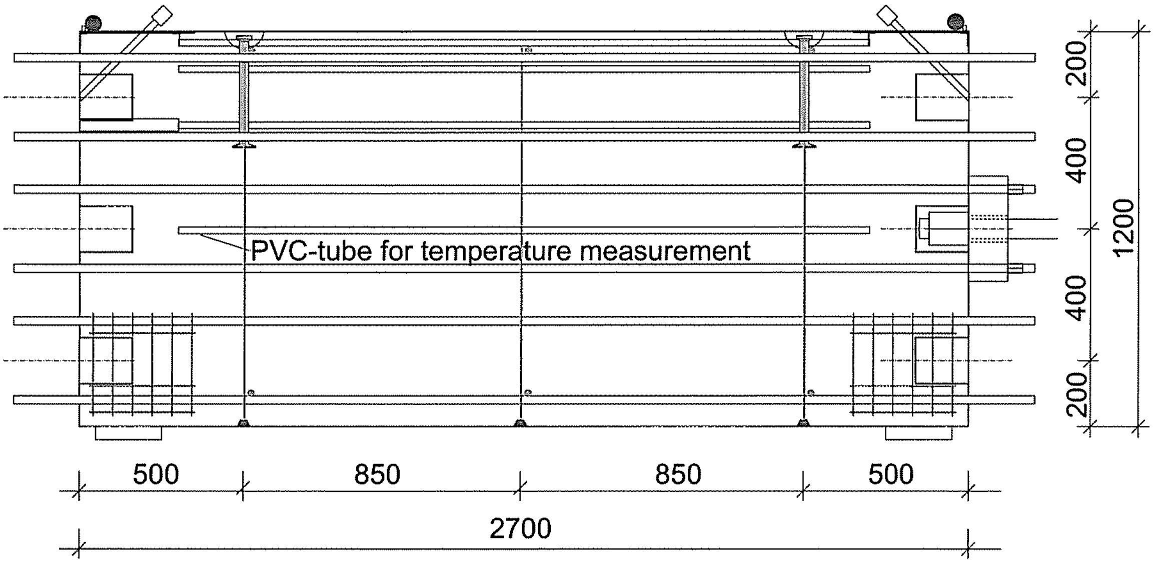

Fig. 6: Vertical section specimen type 1

The second specimen type is equipped with ducts and a surface mesh reinforcement equivalent to the EPR containment design. Fig. 7 shows a longitudinal section through the second specimen type with 2 layers of longitudinal ducts on the external side and one layer of transversal ducts above. A reinforcement mesh is located near both surfaces for crack distribution.

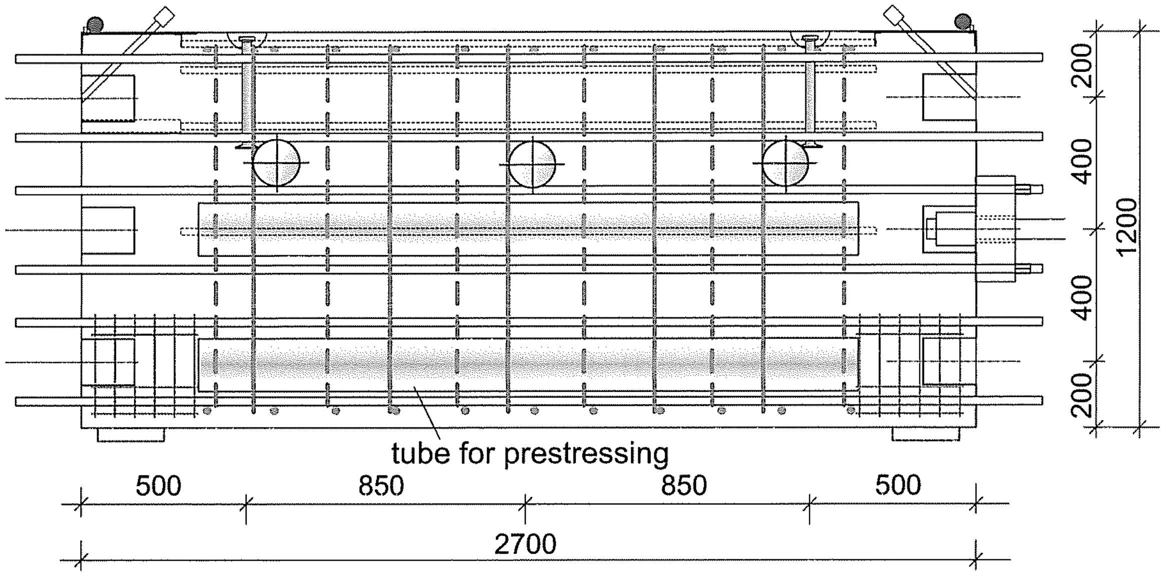

Fig. 7: Vertical section specimen type 2

The longitudinal reinforcement bars of both specimen types are used only for load introduction. The cracks are induced by applying axial tension with the hydraulic jacks. During the tests the external crack width is adjusted by changing the applied load of the jacks and can be modified independent from the pressure inside the pressure chamber.

4 Results

So far, two type 1 specimens and one type 2 specimen have been produced and tested. The first specimen served only to calibrate the air-steam-mixture process.

number of experiment	crack length $[m/m^2]$	mean crack width at external side [mm]	crack widths during experiment [mm]		total leakage [litre water]
			internal side, top (min)	external side, bottom (max)	
VK 2/1	ca. 3,15	"0"	0,007	0,07	0,105
VK 2/2	ca. 3,15	0,15	0,007	const. 0,15	~ 200
VK 3/1	ca. 2,75	"0"	0,005	0,07	1,9
VK 3/2	ca. 2,75	0,30	0,11	const. 0,30	~ 440

Tab. 2: Overview of the performed experiments

4.1 Preparation of specimen VK 2

The second specimen is described for reference of the established testing procedure. It is a type 2 specimen with ducts and a surface mesh reinforcement.

The cracks were induced 139 days after casting applying a maximum axial force with the hydraulic jacks of 7000 kN. The crack pattern obtained is shown in Fig. 8.

Displacement transducers were mounted after crack induction onto the top and the bottom surfaces in order to measure the crack widths during the thermo-hydraulic scenario. If the crack width on the external side varied, it was adjusted by changing the load applied by the hydraulic jacks.

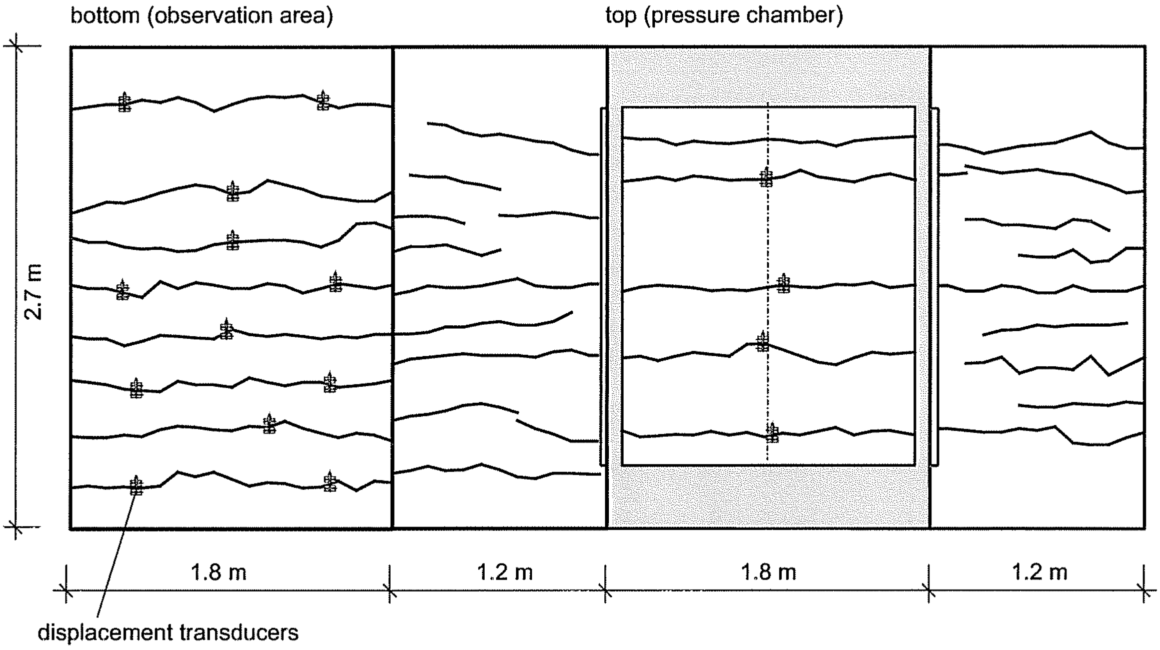

Fig. 8: Crack pattern of specimen VK 2

4.2 Tests with specimen VK 2

The first steam test VK 2/1 was performed with closed cracks without axial load in order to simulate a cracked wall with remaining crack widths only. During the test with closed cracks there was hardly any leakage.

For the second steam test VK 2/2 the average crack width was adjusted to 0,15 mm. The crack width at the bottom surface was kept constant during the whole 40 hour scenario by changing the applied axial load. The crack width change at the top surface side of the specimen followed the temperature inside the pressure chamber (Fig. 9).

The measured leakage rate is shown in Fig. 10. For a better comparability the steam leakage is based on a unit crack length of 1 m, a pressure of 1 bar and a temperature of 0 °C. The steam condensed entirely inside the cracks and no steam outflow was observed. The total amount of leakage during the whole 40 hour scenario was about 200 l of water.

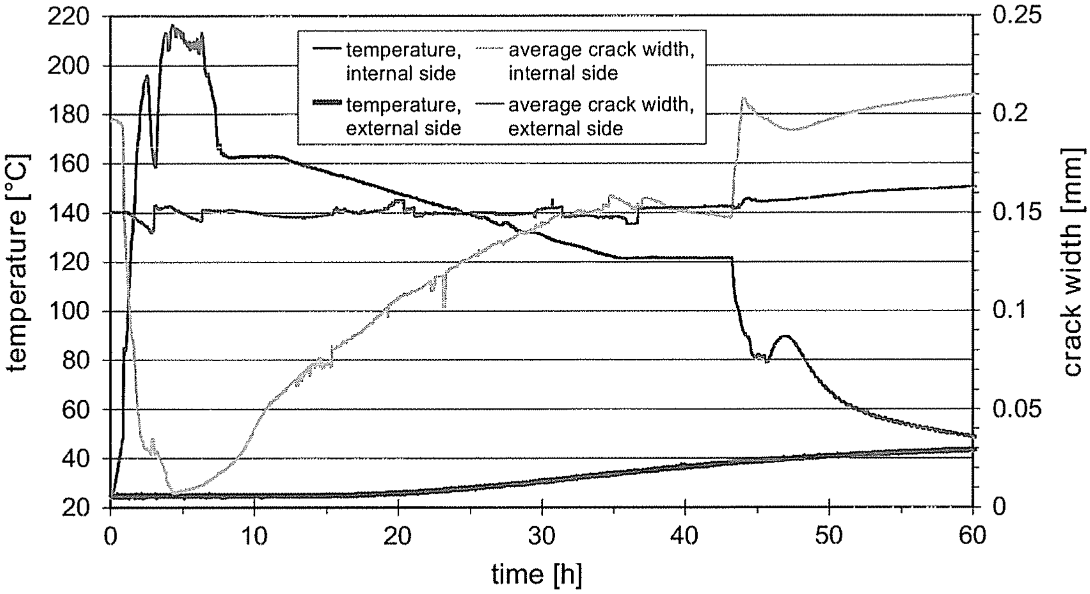

Fig. 9: Temperature and crack width specimen VK 2/2

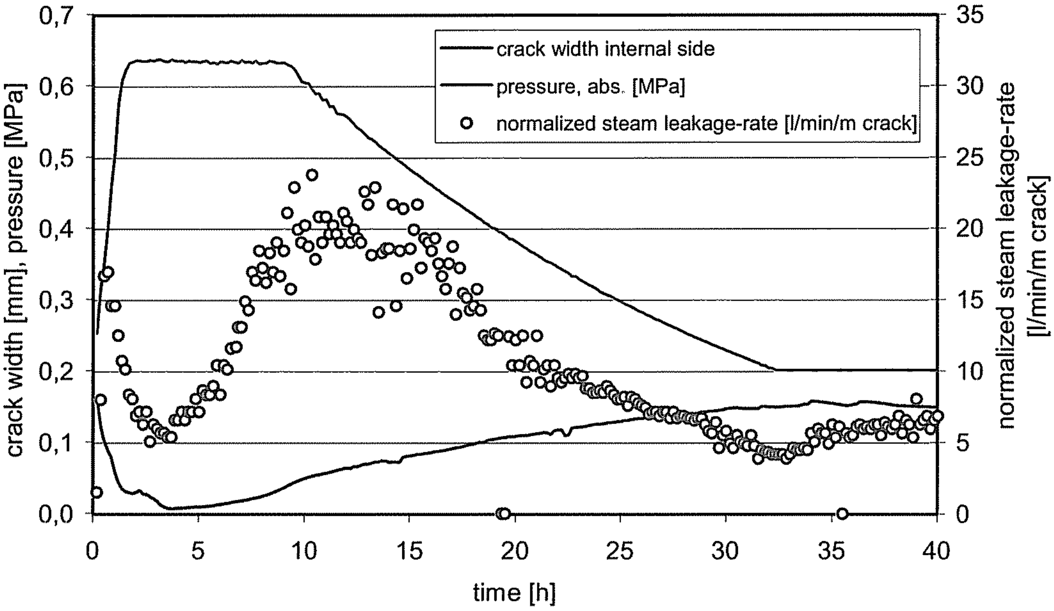

Fig. 10: Leakage of specimen VK 2/2

5 Conclusions

So far four 40 hour tests were performed with 2 different pre-cracked specimen types. During tests with closed cracks no measurable leakage was found. During tests with average crack widths of 0,15 mm and 0,30 mm only water outflow was observed. The steam condensed entirely inside the specimen. The test results can be used for a first estimation of the integral containment-leakage behaviour for a given crack pattern.

6 Literatur

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