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EXPERIMENTAL INVESTIGATION OF THE LEAKAGE BEHAVIOUR OF REINFORCED CONCRETE WALLS

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ABSTRACT

Information about the leakage behaviour of the containment wall of nuclear power plants is of decisive importance for the verification of nuclear power plant safety. In order to study the leakage behaviour of the inner wall of a double walled containment structure under air-steam loads, a model wall section was tested. The wall section is 1,8 m wide 2,7 m long and 1,2 m thick.

The aim of the project was to examine the thermo-hydraulic process of air-steam leakage with possible condensation through known crack patterns. The tests simulate a section of a containment wall and allow to modify the crack width independent from the temperature and internal pressure. Therefore tests at varying crack openings could be performed while using the same load scenario. Additionally to the tests with air steam mixtures pure air tests were performed before, in between and after steam tests in order to compare the leakage rates for the given crack pattern.

A significant reduction of leakage was observed during the course of the tests. This leads to the conclusion that a deterioration of the cracks is occurring. But instead of washing out, the cracks actually get clogged and the flow is reduced.

Keywords: containment wall, air leakage, steam leakage, test, measurement

1. OVERVIEW

1.1 Introduction

Information about the leakage behaviour of the containment wall of nuclear power plants is of decisive importance for the verification of nuclear power plant safety.

So far there are some investigations for the leakage of pure air through cracked concrete specimen introducing correlations depending on crack width and pressure, for instance Greiner & Ramm (1995) or Rizkalla et al (1984). The leakage behaviour of water through cracked concrete specimen had been investigated, too by

Edvardson (1996) or Imhof-Zeitler (1996) for instance. Caroli (1996) performed investigations on the leakage of steam and air through narrow, idealized cracks.

However, corresponding knowledge about the leakage of air-steam mixtures through real cracks with condensation inside the cracks was missing world-wide so far.

Some large scale tests were conducted by EDF (2000) on the MAEVA 1:3 Model. Earlier tests with wall sections were performed at the Universität Karlsruhe (TH) joined by single crack investigations at the Universität Kaiserslautern (Eibl et al., 2001). Results of the first wall tests were published by Herrmann et al. (2002).

1.2 Conception of the experiments

The leakage observation can be divided in mechanical processes leading to cracks through the wall and the thermo-hydraulic processes. The development of crack patterns and the averaged crack widths can be calculated quite well with known numerical procedures like the finite element method. In contrast to the mechanical processes it is difficult to describe the thermo-hydraulic processes inside the cracks like roughness, temperature, heat transfer and condensation.

The aim of the project was to examine the thermo-hydraulic process of air-steam leakage with possible condensation through known crack patterns. In contrast to other investigations on large model containments like MAEVA, it was not intended to simulate the integral behaviour due to temperature and internal pressure.

The tests simulate a section of a containment wall and allow to modify the crack width independent from the temperature and internal pressure. Therefore tests at varying crack openings could be performed while using the same load scenario Fig. 1. Additionally to the tests with air steam mixtures pure air tests were performed before, in between and after steam tests in order to compare the leakage rates for the given crack pattern.

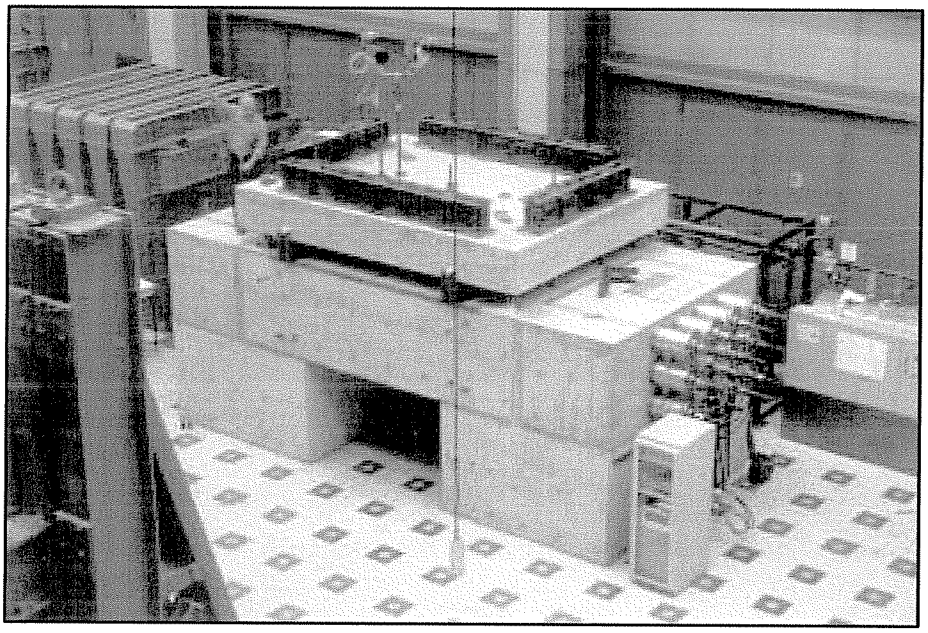

Fig. 1: Total view of the testing facility

1.3 Mechanical set-up

The mechanical part of the testing facility consists of a load frame, two abutments, 12 hydraulic 1 MN 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 anchorage and the abutment for 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 sides of the specimen.

Above the specimen is a steel made insulated pressure chamber, fixed by a reinforced concrete cover and pre-stressed to the load frame. The pressure chamber has an area of 3,28 m² and a volume of about 1 m³. The gap between specimen and pressure chamber is tightened by a rubber seal. A liner at the border area of the upper side of the specimen is used as sealing groove. The air-steam-mixture enters the pressure chamber at one side, passes the surface of the specimen and leaves the chamber at the other side. All flow leaking through the specimen is caught in a control room underneath the specimen. The amount of leakage is measured after the control room.

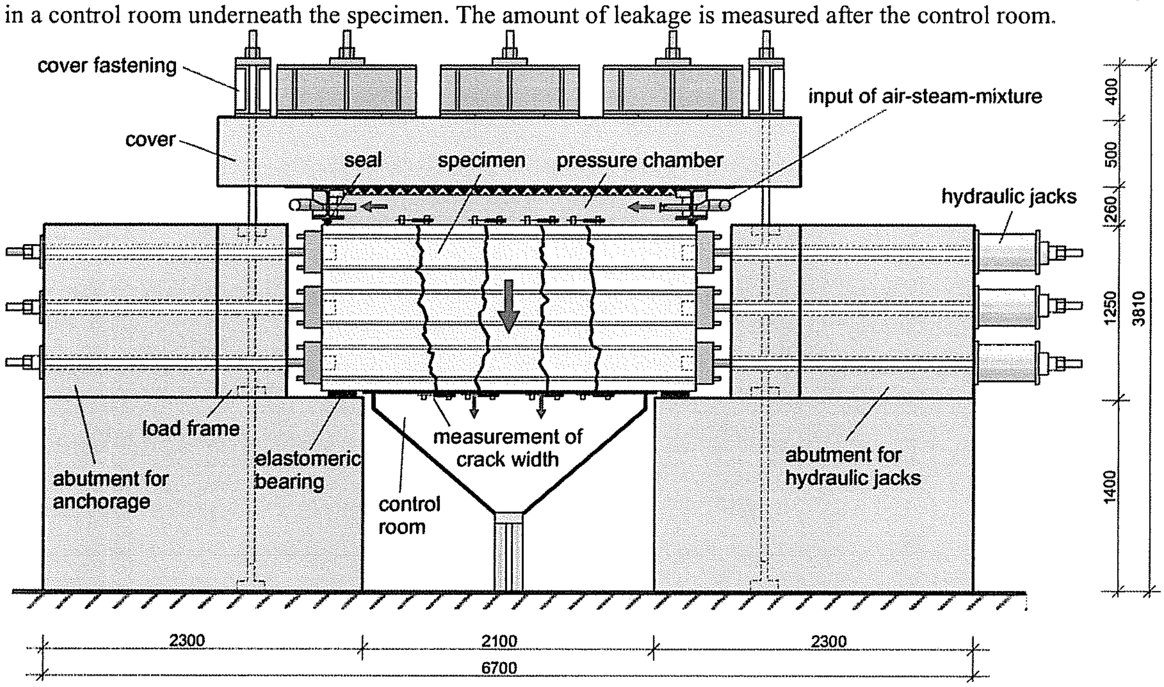

Fig. 2: Vertical cross section

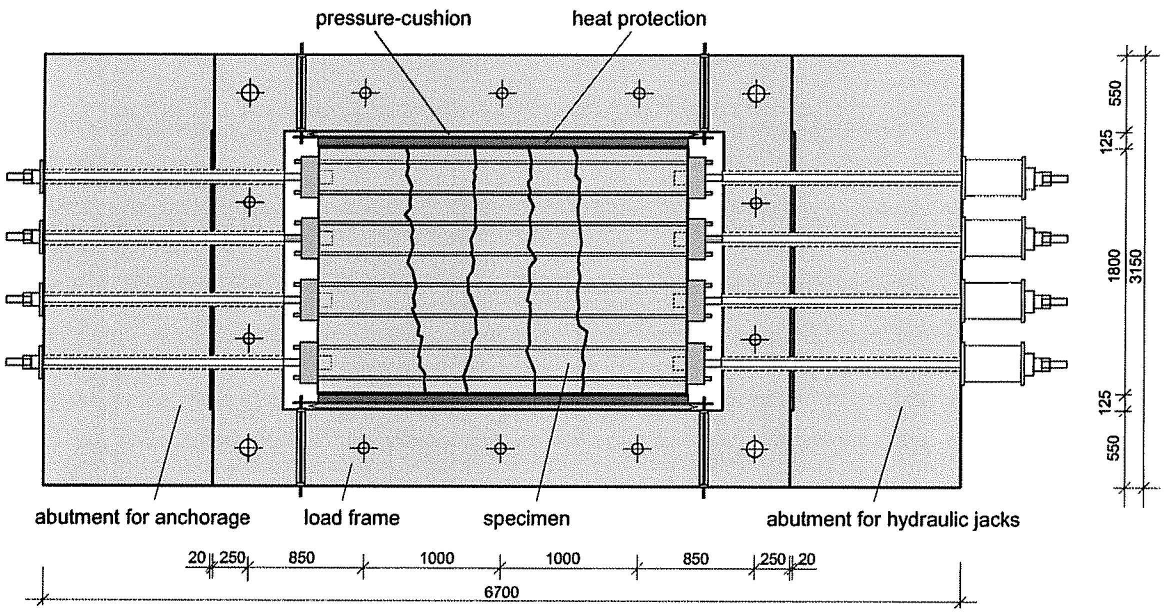

Fig. 3: Horizontal cross section

1.4 Thermo-hydraulic set-up

The aim of the design process of the thermo-hydraulic set-up was to achieve stable air-steam conditions matching complex, highly time dependent scenarios. To fulfil the predefined scenarios it is necessary to regulate the pressure, the ratio of steam and air and the temperature of the mixture. These three parameters describe the physical state completely at any time. The main parts of the machine are the steam boiler, the compressor, the static mixer, air heater, steam super-heater and 3 pneumatic valves.

The machine can be divided into the air channel, the steam channel and the air-steam-mixture channel on the incoming side of the specimen, a bypass channel on the outflow side and the control room to collect leakage. The measurement and control system of the mixture production is realised using four control loops for pressure, air/steam mixture ratio, temperature and flow.

2. MATERIAL CHARACTERISATION

For material characterisation purposes samples were produced together with the specimen and tested. The compressive strength, young's modulus and split tensile strength were tested at cylinders 150x300 mm. The tensile strength and bending energy tests were conducted with beams.

Table 1: Sample test results

	Specimen 1	Specimen 2	Specimen 3
Compressive strength f_{cm} [MPa]	**49,5**	**32,7**	**29,9**
Young's modulus [N/mm^2]	**31400**	**26516**	**24977**
Split tensile strength [MPa]	**4,0**	**3,1**	**2,7**
Tensile strength [MPa]	**3,4**	**3,3**	**3,2**
Bending energy	**124**	**146**	**137**

3. CRACKING A ND TESTING

The specimen is reinforced with 48 GEWI-bars each 25 mm in diameter in order to induce the tension forces into the concrete. At each end of the specimen twelve tension bars are fixed to the GEWI-reinforcement. Those tension bars are used to expand the specimen until the demanded number of cracks is created. Therefore those tension bars are fixed to the load frame at one side and mounted to hydraulic jacks at the other side. To create the cracks it is necessary to produce axial tension in the specimen. Therefore the same hydraulic pressure is used in each jack.

3.1 Creation of the cracks

The creation of the cracks is performed when the tensile strength of the concrete reaches the correct level. The chosen amount of reinforcement bars, their arrangement and their diameter cause three to five cracks if the specimen is strained at a tensile strength of the concrete of $f_{ct} \approx 3$ N/mm^2. The distance between the cracks should be approximately 400 mm. For the creation of the cracks in the specimen the pressure in the hydraulic jacks increases slowly. With the pressure in the hydraulic system the tensile force in the tension bars increases therefore the tensile stress in the specimen increases too. If in some area the tensile stress pass over the resisting tensile strength the first crack over the whole cross section of the specimen will be created immediately. Therefore the forces which were distributed over the whole cross section change to the reinforcement bars only. This causes a fast increase of the tensile stress in the chosen 48 Ø 25 GEWI-reinforcement bars. Because of the amount of reinforcement the tensile stress will increase to a level of 50 % of the proof stress $R_{p0,2}$ only, the deformation of the steel is elastic, it never reaches the yield stress. Therefore the width of the cracks is well controlled and the cracks will be closed nearly completely after decrease of the tensile force in the tension bars. The creation of the other two to four cracks is done in the same way. The Force in the jacks during cracking is shown in Fig. 4. and the crack patterns for specimen 3 are given in Fig. 5.

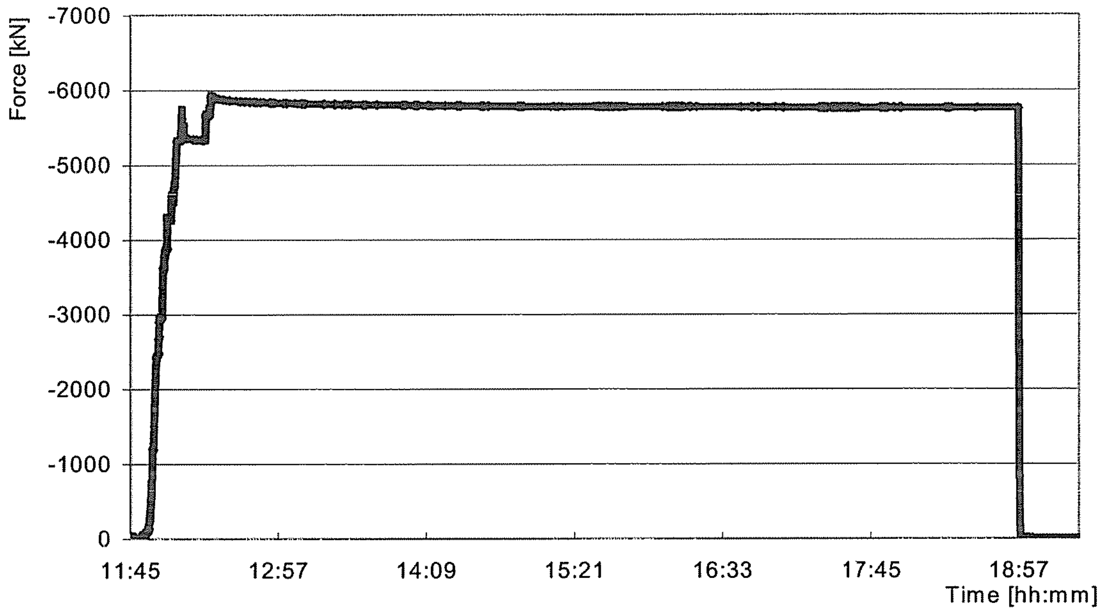

Fig. 4: Jack Force during cracking

Top surface *Bottom surface*

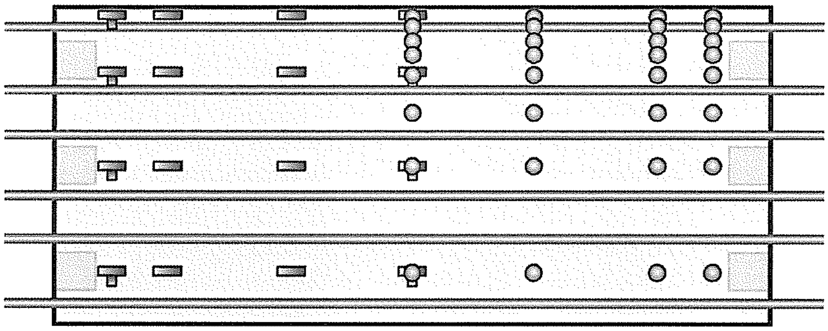

Fig. 6: Layout of the sensors

During the testing pure air-tests and air-steam-mixture tests referred to as "steam tests" were conducted. The thermo-hydraulic load used for these steam tests was a plateau of an air-steam mixture of 1 kg air per 1,7 kg steam at 5,2 bar abs. and 141 °C in the pressure chamber. This plateau was kept for at least 72 hours in order to reach steady conditions.

3.2 Air Tests:

The specimen is placed in the load frame and the cracks at the bottom of the specimen are opened and kept constant via hydraulic jacks to the desired average crack width. After that the pressure in the pressure chamber on the top surface of the specimen is increased in six steps while the escaping air flow at the bottom of the specimen is monitored.

The air tests were performed before, in between and after the steam tests. The Figure 9 shows an example of an air-test. The system follows nicely the scenario and reaches quickly the desired pressures.

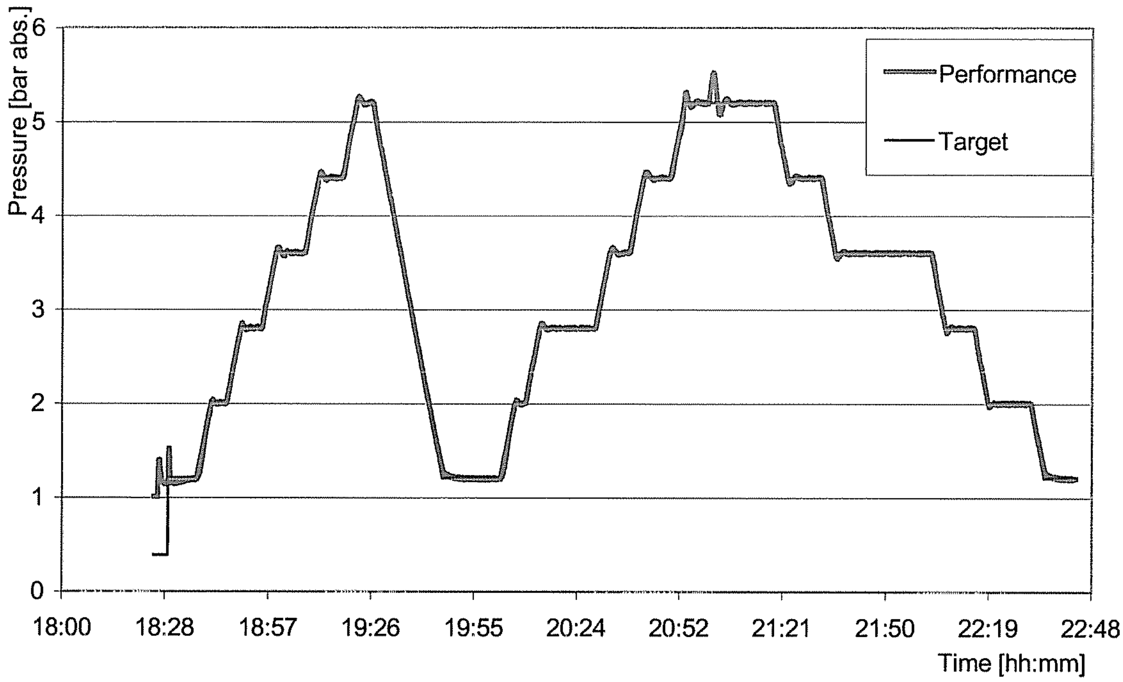

Fig. 9: Performance example of an air test (2nd air test with 3rd specimen)

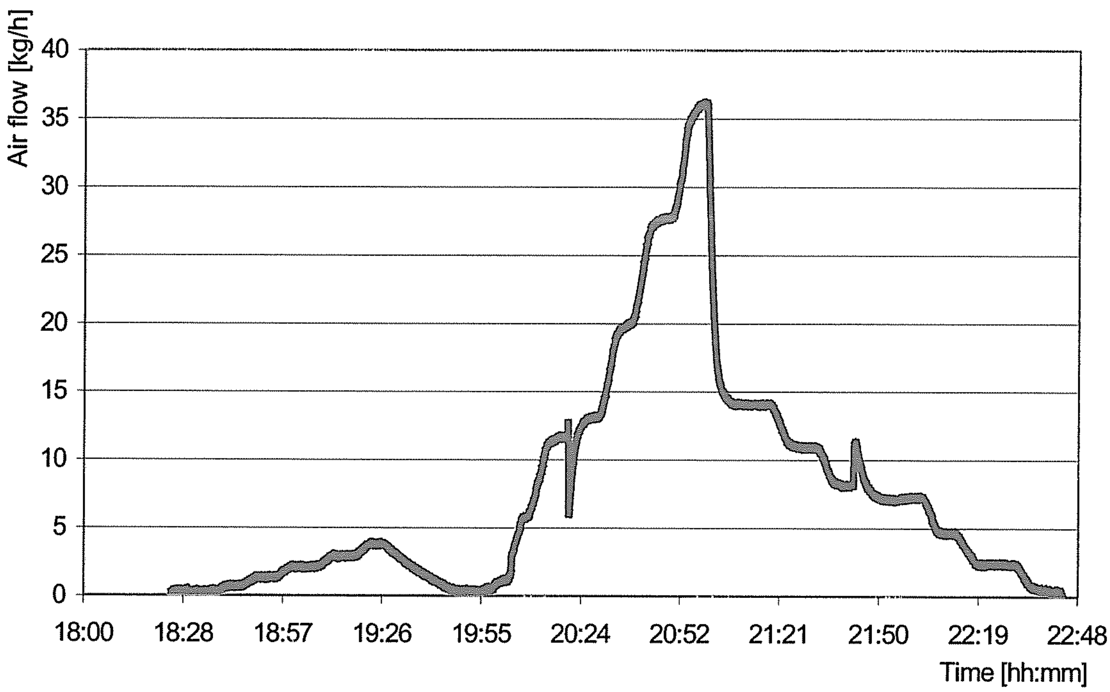

Fig. 10: Air-leakage during air test (2nd air test, 3rd specimen)

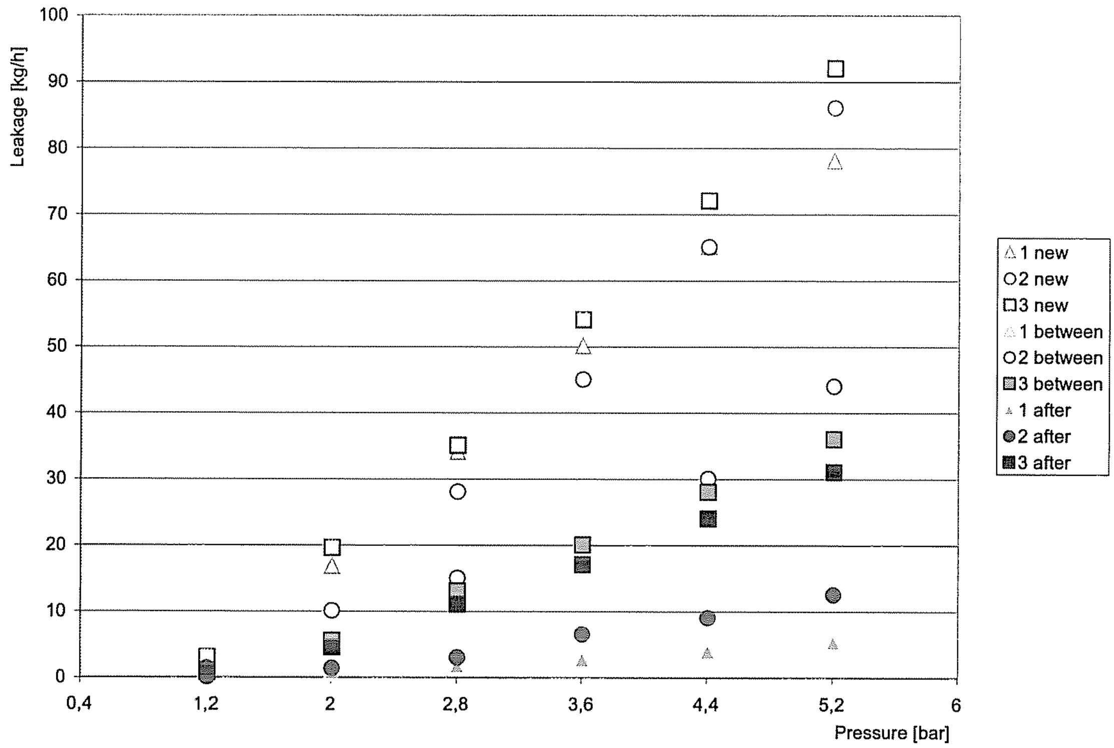

Fig. 13: Flow at w=0,2 mm crackwidth with the specimen 1, 2 and 3

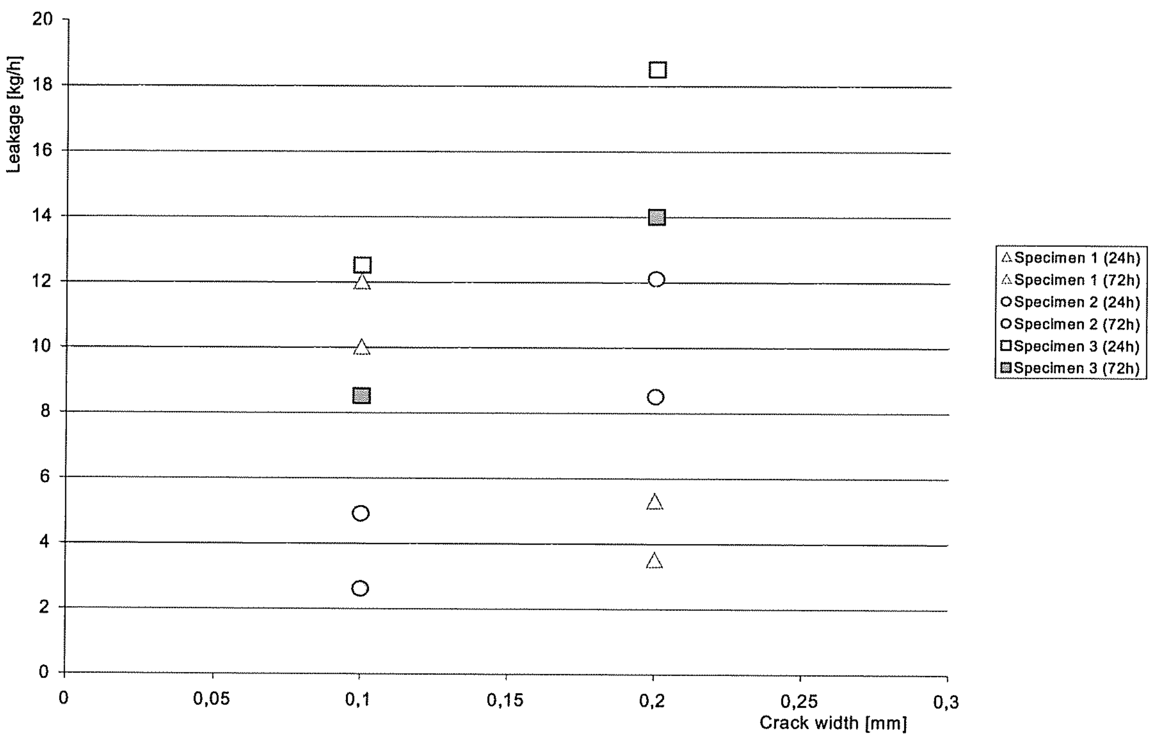

Fig. 14: Total leakage versus crackwidth after one day and at the end of the steam tests

5. CONCLUSIONS

A significant reduction of leakage was observed during the course of the tests. This leads to the conclusion that a deterioration of the cracks is occurring.

Generally the positive effect of blocking reduces the leakage. Regarding the extent of this blocking the Specimen 2 and 3 behave very similar whereas Specimen 1 behaves differently. The main obvious difference of specimen 1 is the use of different aggregates. To determine the chemical or physical effects in the cracks during the tests due to material differences was not scope of the project but it would be useful to investigate this in the future.

In order to quantify these effects and to put these observations on a broader basis further testing should be performed. As of now the predictions of the behaviour must be taken cautious and put into the context of the limited amount of specimen.

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