Experimental study of the behaviour of prestressed concrete pressure vessels of high temperature reactors at accident temperatures

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ABSTRACT

Studies on HTR safety have indicated the great significance of processes resulting during temperature stressing of the pressure vessel concrete for the sequence and consequences of accidents, particularly those with unrestricted core heat-up. The phenomena associated with the release of H_2O (and CO_2 in the case of calcitic concrete) are decisive. Up to now in the main only theoretical investigations have been available for high temperatures and mass concrete. They naturally contain a lot of assumptions and model uncertainties which can only be eliminated by experimental studies.

The aim of the experimental work is to expose representative sections of the PCRV from HTR's to the expected accident temperatures and to investigate the behaviour of the reinforced concrete, the steel liner and the thermal insulation.

1 INTRODUCTION

In medium and large high-temperature reactors the primary circuit is integrated in a prestressed concrete pressure vessel. This vessel consists of concrete several metres thick and is lined on the inside with a gastight steel shell, the liner anchored in the concrete. There is a heat protection system on the liner with insulation on the inside and water cooling on the outside. The pressure is taken up by the concrete, which has been prestressed with horizontal and vertical prestressing cables.

Accidents which might lead to an unrestricted heatup of the reactor core are hypothetical; for the HTR-500 the frequency of such an accident is one in ten million years.

Studies on HTR safety have indicated the great significance of processes resulting during temperature stressing of the pressure vessel concrete forthe sequence and consequences of accidents, particularly those with unrestricted core heat-up. For a core heatup accident it is assumed that all active cooling systems - main cooling system, afterheat removal systems and liner cooling system - have failed. In the course of the accident, the vessel is therefore slowly heated up so that it takes a long time before the failure temperatures of the insulation, liner and concrete are exceeded. As a consequence, water is released from the concrete. This can initiate corrosion processes in the graphitic core involving an additional release of fission products and the possibility of burnable gases being produced. The phenomena associated with the release of H_2O (and CO_2 in the case of calcitic concrete) are decisive. Up to now in the main only theoretical investigations have been available for high temperatures and mass concrete /1/. They naturally contain a lot of assumptions and model uncertainties which can only be eliminated by experimental studies.

The aim of our experimental work is to expose representative sections of the PCRV from HTR's to the expected accident temperatures and to investigate the behaviour of the reinforced concrete, the steel liner and the thermal insulation.

2 EXPERIMENTAL SETUP

In the experiments the sections of the PCRV with an area of 1.0 x 1.5 m and a thickness of 0.5 m were heated by being suspended over an electric chamber furnace (Fig. 1). There are 12 silit heating rods in the furnace chamber which make working temperatures of up to 1500 °C possible so that, if desired, the melting temperatures of steel and concrete can be reached. A preset accident temperature-time curve can be simulated. There are several inspection holes with quartz glass in the sides of the furnace in order to observe the test specimen or make a photographic record of the processes at the test specimen during the experiment.

The test specimens themselves are representative sections cut from HTR prestressed concrete vessels on the original scale. They consist of concrete and liner plate anchored with bolts and cooling pipes. The models are equipped with thermocouples and pressure gauges. The amount of released water and gas is measured as well.

3 EXPERIMENTAL RESULTS

The first two experiments carried out to date have indicated that the models used in risk analyses to describe the behaviour of prestressed concrete pressure vessels for accident temperatures are based on too unfavourable assumptions. Higher failure temperatures than predicted actually occurred in the experiments. Furthermore, greater attention must be paid to the chemical processes taking place during oxidation of the steel parts.

The two test specimens were heated on the liner side to 1410 °C and 1470 °C respectively (Fig. 2). The quantities of water released out of the concrete from 70 °C onwards are measured. In the measured temperature distributions the evaporation front of the water in the concrete is clearly indicated by the two breaks near 100 °C (Fig. 3). The front moves through the specimen.

As expected, the release of CO_2 from the calcitic concrete began at about 600 °C with a maximum near 900 °C. After the test the specimen was sawn into two parts so that one can see what has happened inside the block. The region with CO_2 release between 600 °C and 900 °C could be identified by the black- grey dyeing (Fig. 4). Above 900 °C the concrete has no strength, it is granular and powdered (CaO). At 600 °C the strength of the concrete is still 45 % of the strength at room temperature.

At temperatures above 1000 °C, the liner was lowered perceptibly due to creep, both of the liner itself was well as of the anchoring bolts. At a liner temperature of approximately 1270 °C a scale layer of iron oxide about 3 mm in thickness began to peel off the liner. A hole was formed in the liner at about 1350 to 1400 °C through which molten steel material leaked. In previous analyses, the liner was already assumed to fail at 1000 °C.

The side of the liner facing the concrete also displayed considerable corrosion after the experiment. For example, the bolts were no longer connected to the liner and had in part melted off in the same way as the cooling tubes. In a helium atmosphere, on the other hand, no scaling occurred on the side of the liner facing the furnace. To simulate more realistically reactor conditions the furnace has therefore been altered to maintain a helium atmosphere in the chamber.

4 ANALYTICAL RESULTS

One of the aims of the experiments is the verification respectively the improvement of a code for calculating the water and gas release of the concrete coupled with the temperature distribution in a real PCRV of an HTR nuclear power plant. The code used is the USINT program taken over from the Sandia National Laboratories, Albuquerque, USA /2/. With some improvements especially relative to the models of the porosity and the temperature dependent heat capacity of the concrete it is possible to calculate the release of water and gas as well as the temperatures in good agreement with the measured values.

The highest release rates are found at the beginning of the evaporation; they decrease with increasing temperature respectively time (fig. 5). The totally released mass of water can be seen in Fig. 6.

In the first two experiments only a relatively small pressure build-up due to the water release had been measured. In the next tests special attention is drawn to this point. Published test data show a pressure value to a maximum of about 4-5 bar. The USINT-Code has to be improved to take into account the formation of a crack pattern as a result of the high vapor pressures and the relatively low tension strength $\sim 5\ N/mm^2$ of the concrete.

5 FOLLOWING TESTS

The planned HTR-500 design will be taken as a basis for the test specimens to be examined next. The possibility of refeeding the liner cooling system - assumed to have failed - will also be studied. This is of great significance since damage to the prestressed concrete reactor pressure vessel can be avoided by a restart.

6 CONCLUSION

These experiments create a basis for treating core heat-up accidents more realistically than has been possible in the past. Any system simplifications resulting from these results will still have to be examined.

REFERENCES

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Prestressed Concrete Pressure Vessels under Hypothetical Accident Conditions.
Beck, J.V. and Knight, R.L. 1980. User's Manual for USINT. NUREG/CR-1375, SAND 79-1694.

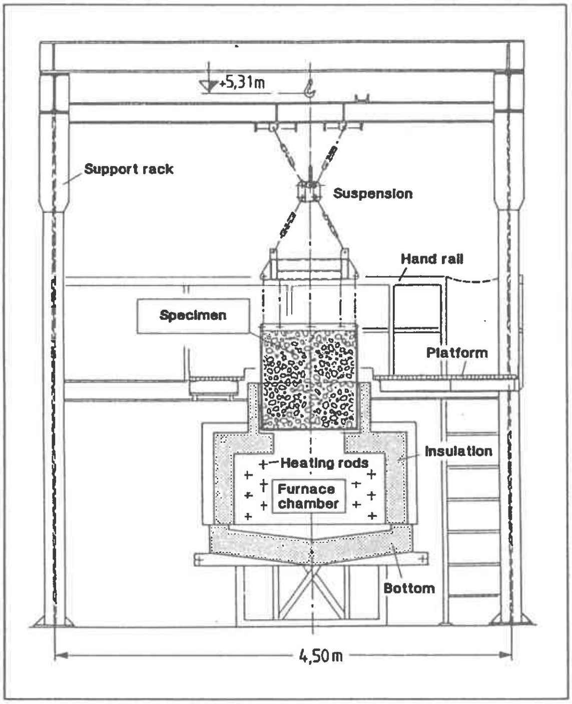

Fig. 1: Experimental setup

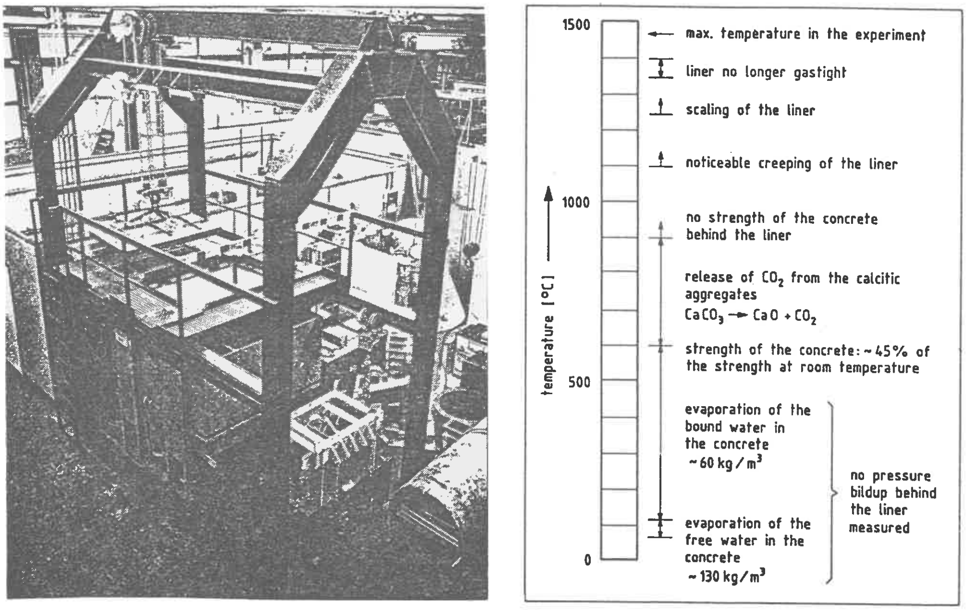

Fig. 2: Summary of the test results and view of the experiment

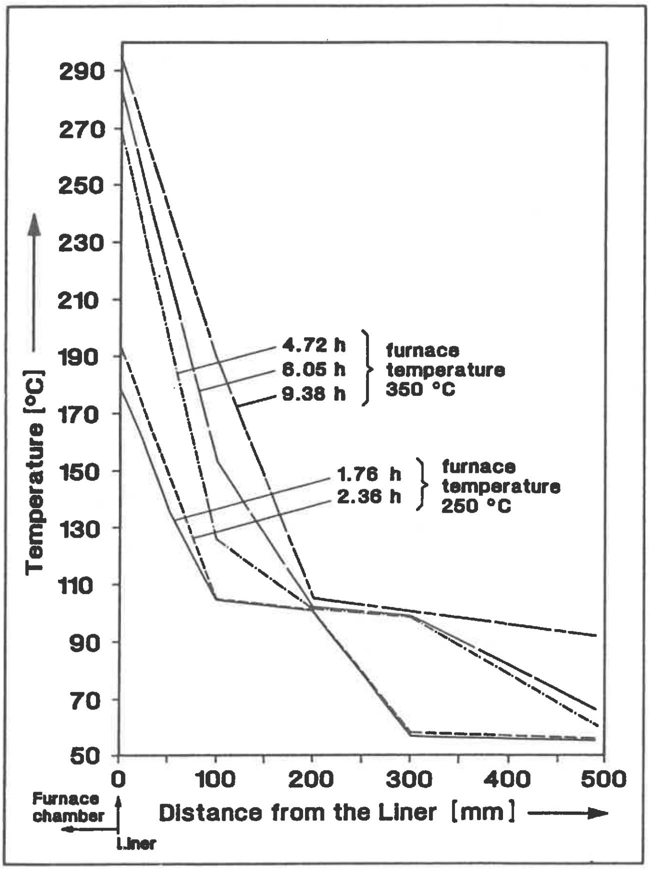

Fig. 3: Measured temperature distributions within the specimen

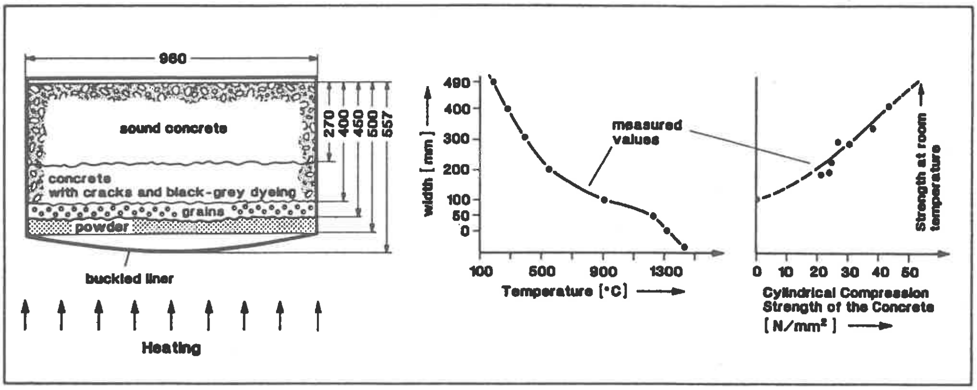

Fig. 4: Condition of the concrete after the test dependent on the temperature

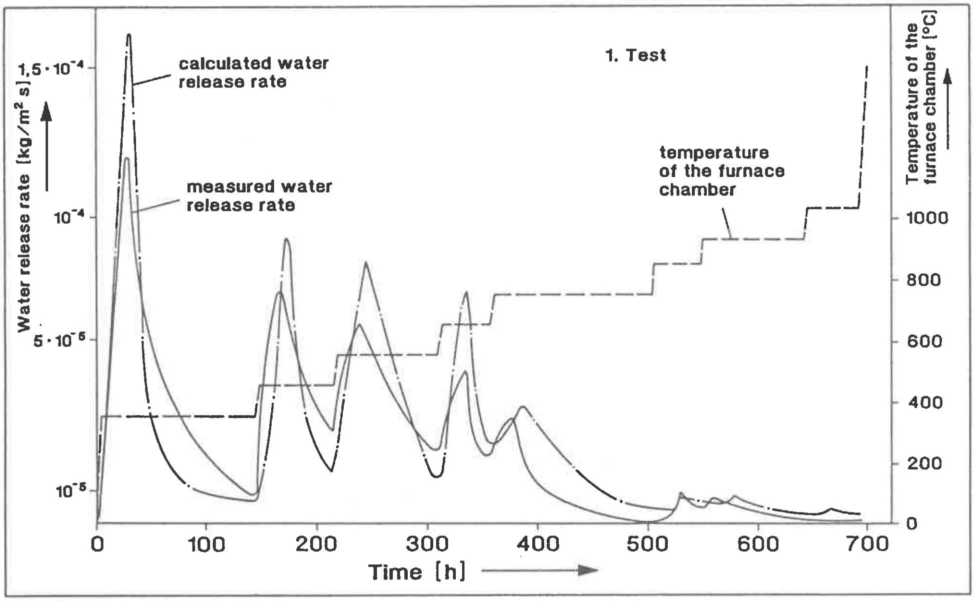

Fig. 5: Water release rates during test 1

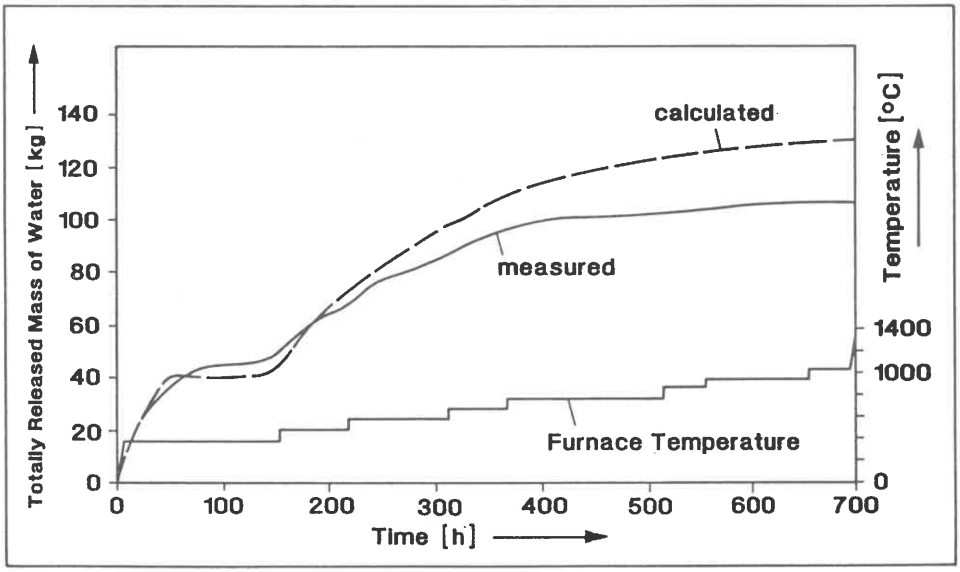

Fig. 6: Totally released mass of water out of the concrete during test 1