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THERMAL ANALYSES OF INWA-EXPERIMENTS FOR MODULAR HTR-REACTORS

A. Kneer[1], W. Häfner[1], P. Hejzlar[2], R. Schulz[1] and L. Wolf[1]

[1]Battelle Ingenieurtechnik GmbH, Frankfurt/Main, Germany
[2]MIT, Dept. of Nuclear Engineering, Cambridge, MA, USA

1 ABSTRACT

In order to reduce the residual risk of catastrophic reactor pressure vessel failure of modular HTR's in case of loss of core cooling functions, an alternative RPV has been proposed and designed by the firm Siempelkamp, Krefeld, FRG under the sponsorship of BMFT. This alternative RPV design is fabricated of high quality, ductile sphero cast iron components with pre-stressed axial and circumferential tendon packages.

This specific Siempelkamp design has been tested and qualified in a series of experiments with the sample test vessel. This design was also used for the control gas vessel in the THTR under operational service conditions.

In order to further mitigate loss of heat sink functions, a natural circulation system was designed for cooling the cavity cell structure by embedded tubes in the cast iron cavity structure.

In order to demonstrate reliable decay heat removal under most severe conditions, a 1 : 1 scale, 20 ° sector of the vessel/cavity, termed INWA-facility (inactive decay heat removal) was fabricated and tested at Siempelkamp.

A total of 6 experiments were performed with this setup examining a variety of changes in constructive details, surface and cooling conditions. Each experiment was performed both for operational conditions and depressurization transients, typical for a 200 MW_{th} HTR-module. Experimental test durations ranged up to 1000 hours. The last experiment tested the common steel vessel design.

**Pre- and post-test calculations with the FEM-code TOPAZ accompanied the INWA test series.
This paper describes the INWA-facility and the experimental results as well as the predictive capability of the TOPAZ-code by comparing the data with computational results.**

The INWA-results qualify the pre-stressed cast iron vessel together with the natural circulation cooled cavity even for the worst of severe accident conditions. Even in the case of a total failure of all cooling capabilities in or at the cavity structure the vessel surface temperature remains below critical values.

The paper summarizes the results of the experiments and accompanying computational analyses for a number of generic issues all of which are related to the search of passive cooling systems of future advanced nuclear reactors.

2 INTRODUCTION

Since 1973, the design and planning of German pebble bed high temperature, gas-cooled reactors was accompanied by the alternative reactor pressure vessel design using the concept of prestressed cast-iron (PCI) vessel [1]. In 1975, developmental work started and in the following years, it was demonstrated that PCI-vessels can be operated up to 350 °C.

In late 1987, the firm Siempelkamp proposed [2] such a combination of a reliable pressure vessel construction with the advantages of a passive decay heat removal system fully integrated into the reactor silo cell structure.

This proposal was based on the design features and overall measures and characteristics developed by SIEMENS/KWU (INTERATOM) for the 200 MW_{th} HTR-modular reactor design, with the substitution of the PCI-vessel for the common steel vessel and to replace the silo structure by the composite cast-iron/concrete structure developed by Siempelkamp [2, 3], as described in the following.

3 INWA-TEST FACILITY

Fig. 1 gives a perspective view of INWA Test Facility which corresponces to 20° sector of a 200 MW_{th} Siemens/KWU HTR modular pebble bed reactor design. The test facility was constructed with all details of a realistic PU-vessel and cast iron/concrete composite structure with circumferential tendon reinforcement at a scale 1:1.

The height of the sector was chosen to be about 2 m - only a fraction of the total axial system extension. Therefore, natural circulation condition in the embedded tubes had to be simulated accordingly by appropriate forced convection condition.

In order to provide an ultimate heat sink in case of failure of both redundant, natural circulation piping systems, a film cooling device, see 10 in Figure 1, was installed in order to rinse down on the outside reactor cell composite surface.

The complete INWA-facility was embedded within 500 mm thick thermal insulation. Also, as shown in The driving thermal power is provided by the electric heater element, see item 1 in Figure 1. This heating element consisted of 4 independently controlled heating circuits to assure a surface temperature as uniform as possible by properly accounting for the end heat losses.

4 MEASUREMENT SYSTEMS

In order to reach the full objectives of the INWA-tests, the complex three-dimensional structure was instrumented with a total of 123 embedded and surface thermocouples, the majority of which were placed along the radial centerline of the sector. Furthermore, to obtain temperatures and heat fluxes across gaps and contact interfaces between components, the emphasis in the instrumentation was put on the positioning of a sufficient number of thermocouples at the relevant surfaces and in the wire packages. Furthermore, to evaluate the heat loss properly, a number of thermocouples were also placed towards the boundary sides of the facility.

Special instrumentation were positioned inside the cavity in order to determine the temperature distribution, velocity fields and radiative transfer. For this purpose, 3 globe thermometers, 4 turbine anemometers and special thermocouples were installed at movable rakes.

4 calorimeters were installed into the embedded cooling tubes.

All measurement signals were sampled, converted and documented by a PC-based measuring system.

5 OBJECTIVES AND TEST MATRIX

As demonstrated in Fig. 1 the heat removal through the INWA- facility is of complex nature. There are gaps, wholes, the cavity cell and the wires which make understood that the heat transport processes occurring in the different parts of the PCI-vessel and composite reactor cell structure need to be fully analysed.

With these informations as background, the objectives of the INWA-experiments were as follows:

(1) Demonstration of reliable and predictable passive heat sink capability under operational and accidental reactor conditions without endangering (thermal limits) individual components and the integrity of PCI-vessel structure.

(2) Determination of appropriate values for thermal resistances, thermal conductivities (axial and circumferential packages of cable wires), and heat transfer coefficients at various interfaces.

(3) Evaluation of the importances of convectlve and radiative heat transport mechanisms in gaps, most importantly across the cavity.

(4) Determination of the effects of changes in constructive details (addition of a protective cover plate shielding the circumferential cable package, surface treatment by adding a black coating onto the surfaces facing the cavity).

(5) Evaluation of the impact of total failure of the natural circulation heat sink capability and/or cell outside surface film cooling on the thermal responses of the PCI-structures and the composite reactor cell structure.

A total of 6 experiments have been performed and evaluated thus far, testing the PCI-vessel structure under different conditions cited above (Tab. I).

The last experiment was a reference test with a section of a typical steel vessel for direct comparison and demonstration of PCI versus steel vessel.

All experiments were performed using the heat flow depicted in Figure 2 for controlling the heater plate in order to reach steady-state operational conditions and to simulate accident conditlons according to the predicted behavior during a depressurization accident of the modular HTR-reactor designed by SIEMENS/KWU. The curves shown in Figure 2 account for heat losses (20 %) of the INWA-facility.

6 EXPERIMENTAL RESULTS

Fig. 3 presents measured axial temperature profiles for different circumferential angles at the outer surface of the heat-plate and inner surface of the liner. While the heat-plate profile demonstrates only a small dependence in height and circumferential direction, the liner shows a variation of 25°C in height. This results from natural convection in the gap between the heat plate and the liner and heat losses to the bottom.

Fig. 4 to 5 present measured temperature profiles through the PCI structure for steady-state normal operation and depressurization transient for experiments (0,) 2, 3 and 4. These figures show the results of all experiments without protective cover plate shielding the hoop prestressing cables. As the test facility is modulary constructed, the steps in the temperature profile result in thermal resistances at the different contact surfaces and in the gaps. The comparisons between individual curves in the respective figures clearly demonstrate the limited variation in the experimental results, indicating consistency and plausibility of the data despite of thousands of hours of operation of the INWA test facility. Under normal steady-state operation maximum temperatures at the liner surface range around 275 °C (Fig. 4).

Maximum liner temperatures reach a value of about 470 °C (Fig. 5). For experiment 4 the radial temperature gradient decreases towards the cylindrical rib of the outside PCI vessel surface because this experiment was performed without the natural circulation system in the composite reactor cell structure. The simulated failure of this system leads to an increase of the inside cavity surface temperature and as a result to a reduction in heat transport across the gap. In this case the gap temperature level increases from around 150 °C for experiments 2 and 3 up to 220 °C in experiment 4. The outside film cooling of the cavity reduces cavity temperatures by around 15 °C and does not have a significant influence on heat removal.

During experiment 1 a zinc coated cover plate, shielding the hoop prestressing cable was mounted. It is obvious that the cover plate represents a large heat transfer barrier to the cavity cell. Therefore the temperature levels in the PCI vessel increased to considerably higher values [6]. Cable temperatures rise from 250 °C to 380 °C. In consideration of the yielding point, a high value must be set on the selection of the prestressing cable material. The results of experiment 1 necessitated in the removal of the coverplate for the following series of experiments.

This change in construction manifested the importance of the thermal conductivity of the hoop prestressing cables. The heat conductivity of the cables can only be interpreted as a resultant thermal conductivity including radiation effects.

- after experiment 1 the resultant conductivity has changed to lower values.
- the resultant conductivity is depending on temperature (thermal radiation effects).
- the resultant conductivity decreases from experiment to experiment which results in a small destressing of the bundle structure.

An averaged value for the resultant conductivity of 3.5 W/m/K was assumed for pre- and postpredictions [6].
In order to analyse the heat transport processes across the cavity cell the radiative versus convective transport have been evaluated. The importance of radiative transport (92-97 %) is much more important as the convective (3-8 %) transport [6].
The heat losses to the environment and to the bottom reached values of about 30- 50 % of the heat input.

7 ACCOMPANYING NUMERICAL ANALYSES

All INWA-experiments were accompanied by computational analyses with the FEM-code TOPAZ. The TOPAZ-code was extended by including 2D radiation properties using the FACET-methodology [5] to derive the multi-dimensional view factors.
A horizontal cut through the test- facility has been choosen as the modelling plane for nodalization and computations.
Figure 6 show for INWA-experiment No. 4, respectively, that after a substantial learning period [3], the optimization of the code input parameters result in excellent agreements between measured data and computed results. Even worst-case scenarios, with failure of all cooling systems, as tested during experiment No. 4, can now be predicted with confidence as depicted in Figure 6. The results of the calculations by comparison with the experimental data could be used to verify the contact resistances between the contacting surfaces of the test facility.

8 CONCLUSIONS

The large-scale INWA-experiments have achieved all their objectives with a high level of confidence. Most importantly they demonstrated the passive heat removal capability of the combination of PCI-vessel and composite reactor cell structure for the specified conditions examined in full scale.
Detailed insights obtained from the experimental data allowed the proper specification input parameters for TOPAZ code predictions, that were not readily available previously.
Measurement and evaluation techniques were fully tested at high temperature levels and during hundreds of hours for each experiment.
The experiences gained from these experiments may well supplement the design needs of reactor cavity cooling systems developed elsewhere. The facility is available for more and possibly different experiments in the framework of an international cooperation.

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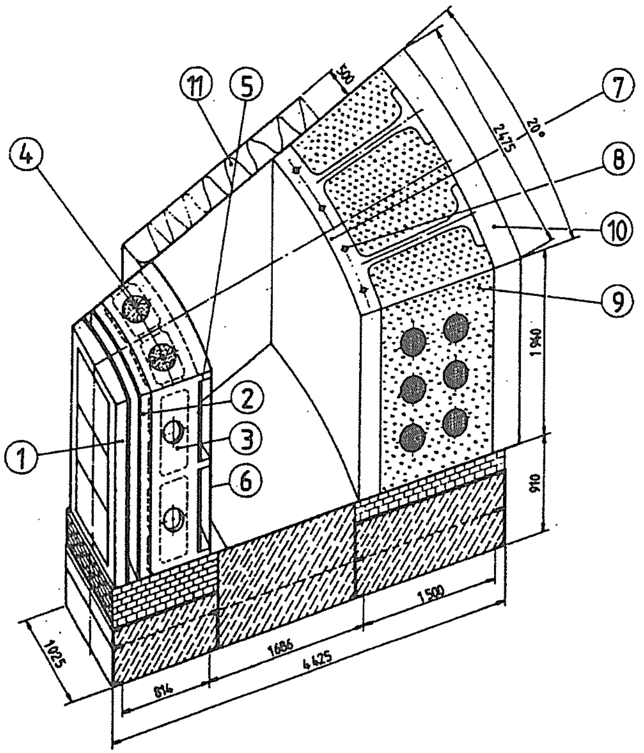

1 Electric heater and core vessel
2 Liner
3 Pressure vessel wall
4 Axial prestressing tendon
5 Hoop prestressing cable
6 Cover plate
7 Cast iron block of the reactor cell
8 Cooling system
9 Reinforced concrete
10 Sprinkler system
11 Insulation

FIG. 1 INWA-TEST-FACILITY

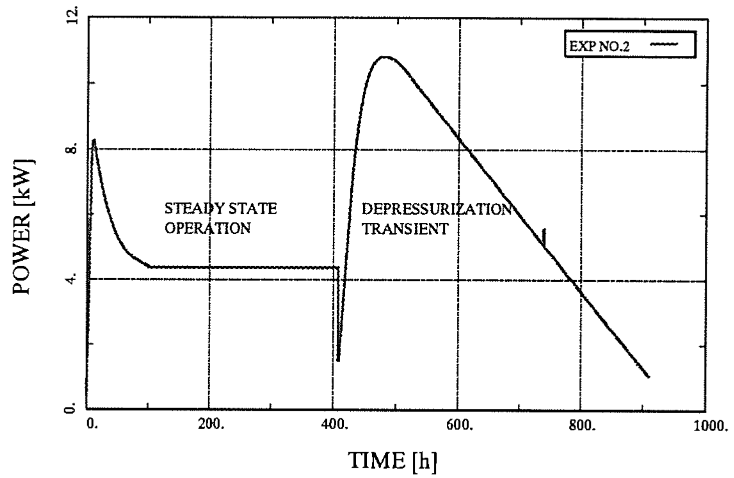

FIG. 2 Generated heat flow

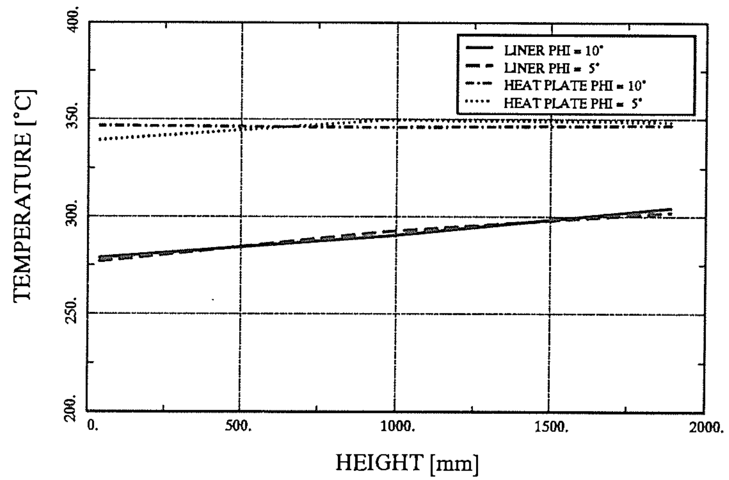

FIG. 3 Vertical temperature distribution
Exp. No. 2 / Normal operation

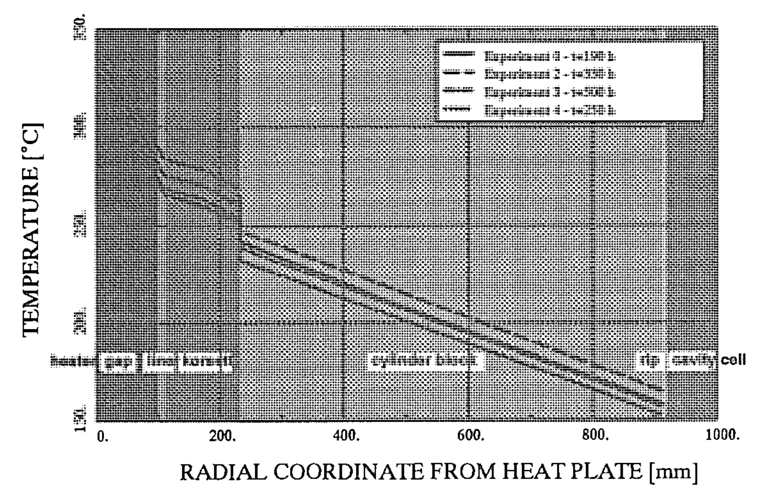

FIG. 4 Normal operation
Cylinderblock temperature profile

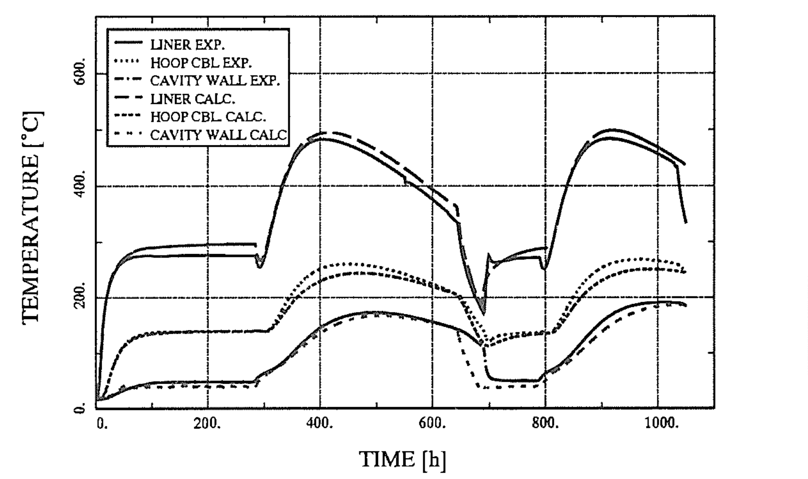

FIG. 6 Comparison of measured and calculated data
Experiment No. 4

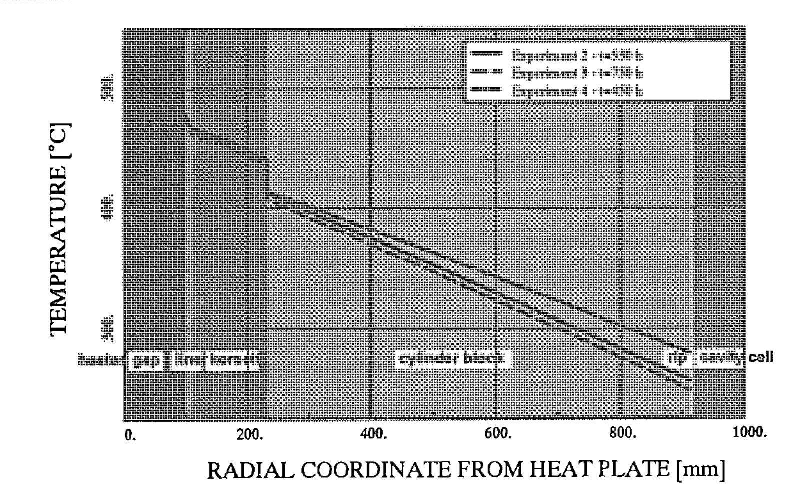

Fig. 5 Depressurization event
Cylinderblock temperature profile

Exp. No.	Description	Cooling	Film Cooling
0	Heat flux increase (10 %) 200 h to 370 h	on	off
1	Start of the DPE at 604 h Experiment with cover plate	on	off
2	Start of the DPE at 408 h	on	off
3	Start of the DPE at 577 h Black coating onto the surfaces facing the cavity	on	off
4	Start of the 1.DPE at 283 h Start of the 2.DPE at 788 h Black coating onto the surfaces facing the cavity	off off	on off
5	Start of the 1.DPE at 100 h Start of the 2.DPE at 350 h Steal vessel instead PCI-vessel	on off	off off

DPE = Depressurization Event

Tab. I Test matrix