Special Aspects on the Behavior of PCRV Under Extremely High Core Temperature Loading

K. Schimmelpfennig
Zerna, Schnellenbach u. Partner, Gemeinschaft Beratender Ingenieure GmbH, Viktoriastr. 47, D-4630 Bochum 1, Germany

J. Altes
Institut für Nukleare Sicherheitsforschung, Kernforschungsanlage Jülich GmbH, Postfach 1913, D-5170 Jülich 1, Germany

A paper presented at the 6th Conference on SMiRT /1/ dealt with investigations on the behaviour of the PCRV for the HTR 1160 MWe nuclear power plant subjected to a hypothetical accident with unrestricted core heatup following loss of forced cooling. The progressive degradation of the vessel top head under the extremely high core temperatures had been demonstrated by use of detailed calculation models. In these calculations a layer of concrete was assumed to fail at a temperature where the strength of concrete or reinforcing steel, respectively, is getting zero due to the temperature increase, neglecting the actual states of stress. In the present paper, firstly this assumption is substantiated by showing analyses of the overall behaviour of this HTR vessel using an adequately simplified model, which demonstrate that indeed concrete layers adjacent to the inner surface are unloaded due to stress redistribution effects to such a degree that concrete compressive strength - although also decreasing with increasing temperature - never will be less than the existing stress.

Furthermore, the paper deals with corresponding investigations on a PCRV for a certain HTR with pebble-bed core planned in Germany. For this plant, additional studies on the failure mode of the top reflector and the top thermal shield and possible influences on the temperature conditions in the core cavity had to be carried out, because unlike the HTR-1160 in this case these components are suspended on the vessel top cap necessitated by the pebble-bed concept. Because of the failure mode found for the top reflector there is no difference in the following process whether the top reflector is assumed to be intact or not. Failure of the thermal shield, however, yields a significant temperature rise in the gas plenum below the PCRV top cap. If the liner cooling systems remains intact during the accident sequence the temperatures will stabilize at a level below 900 °C, which has been found to be the failure limit of the top thermal shield. In this case, no failure of the top cap with its liner and insulation will occur. On the other hand, if the liner cooling does not operate, failure of the thermal shield will occur after 170 h, thus 1200 °C gas temperature being admitted to the PCRV insulation. This leads to progressive failure of the vessel top cap during the following time. The resulting spalling-off sequence has been calculated corresponding to the procedure used for the HTR-1160. Some characteristic computer plots are shown. The amount of concrete spalled from the vessel walls is compared with the previous results of the HTR-1160 vessel.

1. Introduction

Probabilistic risk assessments /2/ /3/ /4/ for HTR plants showed as a result, that the PCRV and the possible sequences of its gradual failure are of great importance to the consequences of hypothetical accidents with unrestricted core heatup. Hence, it has been desirable to verify the simplified procedures used in these studies for analysing the PCRV response by more accurate methods. The present paper deals with several main topics of these investigations in addition to the presentation at the 6th Converence on SMiRT /1/. The research work on this subject has been funded by the Minister for Research and Technology of the Federal Republic of Germany (ref. RS 447) and carried out by the authors' institutions together with the Institute for Structural Materials, Concrete Construction and Fire Protection of the Braunschweig Technical University.

It has to be pointed out that the analysed accident belongs the hypothetical ones with a very low probability of occurence.

2. Overall structural behaviour of a PCRV during core heatup accidents

2.1 Object of the investigation

Within the detailed failure propagation calculations, dependence of the degradation process on the actually existing states of stress has been disregarded, as already mentioned. This means it has been assumed that at each point of the structure and at each moment the existing stresses are lower than the instantaneous local material strength. Thus, with an accident temperature transient as shown in /1/, Fig. 4, a progressive degradation takes place, after the insulation has failed at the time t = 95 h, with concrete layers being spalled up to 0.63 m depth until t = 245 h, the end of the analysed space of time. (For details of these investigations see e.g. /5/).

In order to proof the validity of this result it had to be shown, however, that indeed the degradation is not influenced by the structural behaviour of the overall vessel together with local stresses due to temperatures. This is the subject of the following section.

2.2 Computational procedure and results

Stress calculations with the aim mentioned above were carried out for a few representative states. An important state is e.g. that one immediately before failure of the insulation. It had to be checked, whether perhaps a significant amount of concrete layers near the inner surface will fail earlier than the insulation leading to a more rapid degradation in the following time. In order to limit the effort, these investigations were carried out using an axisymmetric calculation model for the overall vessel structure supplemented by an analysis of the local stresses around the stand pipes as explained later. In the axisymmetric model - see Fig. 1 - the stiffness of regions bounded by the alignments of the cavities and channels in the side wall has been reduced according to the volume percentage of the hollow spaces, which is admissible, because the main interest is focussed on stresses in the top head and otherwise only the global response had to be involved. For the region of refueling penetrations a fictitious stiffnes was calculated according to /6/, which allows to consider this zone being homogeneous and isotropic. In the same way, a fictitious thermal expansion coefficient was formulated for this region.

Accident analyses started from operational conditions at two different times of vessel life, i.e. the state after commissioning and the state at the end of vessel life.

The temperature dependent material properties used in these stress calculations and in the temperature calculations for local regions will not be discussed here. About this topic it may be referred e.g. to the publications /7/ and /8/. Whithin the stress calculations, particularly the so called transitional creep during instationary heatup sequences has been taken into account, see /8/. The computer program used is based on the dynamic relaxation method, see e.g. /9/. Superposition of the states of stress and strain under service load and accident load conditions was done in a way that the service load portions were influenced by transitional creep, too.

Here, only results for accident initiation at the end of vessel life, where stresses are insignificantly higher, shall be presented, and from the states during the accident only that one at t = 95 h shall be discussed here. The accident temperatures have a significant influence on the states of stress (Fig. 2) and yield high compressive stresses near the inner surface; but these reach only a small portion of the stress values which would have been gained without regarding creep - especially transitional creep -, namely roughly estimated 25 % in the present case. As shown by Fig. 2, at this time the maximum of compressive stresses is no longer situated directly at the inner surface, but in about 0.8 m distance from the surface. This means, that stress redistributions due to transitional creep have already caused a significant unloading of the outer layers. Since temperatures increase in the direction to the surface (actually 673 °C in the first row of mesh points, 408 °C in the second) and strength decreases with increasing temperature, possibly the state of stress near the surface may be more critical, although stresses are lower. Thus, the detailed investigations described below were carried out for sections with different distances from the surface.

Starting from the mean stresses in the stand pipe region gained by the above mentioned calculations, the real stresses in the concrete between the refueling penetrations were analysed using a disc model for a single pipe together with the surrounding concrete. Comparison of the calculated stresses with stress limits showed that only 60 % of the corresponding concrete strength are reached in the section with the highest compressive stresses and that the stress-strength relation is signifcantly higher in the outer section but also here structural failure is not expected.

On the whole, it can be concluded that at least up to the time t = 95 h stress related structural failure can be excluded. This confirms the time of insulation failure at t = 95 h. In the following time, the outer layers of concrete get substantially higher temperatures, because they are directly exposed to the cooling gas. Thus, it cannot be excluded that concrete stresses reach the concrete strength. Spalling of a concrete layer, however, is determined by failure of the reinforcing net below this layer (as assumed in the failure propagation calculations), since the reinforcement is retaining the concrete in place, although it has already failed. Even under pessimistic assumptions for concrete failure, at most a region of about 0.9 m depth does no longer participate in load carrying. Up to this depth, however, there is enough reinforcement, and the residual thickness of the top cap makes shure that an overall failure of the PCRV caused by the prestressing forces will not occur. Hence, the failure model described in /1/ and in section 2.1 of this paper is confirmed by these calculations.

3. Failure sequence in a plant with pebble-bed core

3.1 Preliminary remarks

The components inside the core cavity of a HTR with pebble-bed core (see Fig. 3) are substantially different from those of the HTR-1160 with its block type fuel elements. While the block type core structure of the HTR-1160 allows the placing of the reflector elements directly onto the fuel element blocks, the pebhle-bed core makes it necessary to arrange these elements without any support at the lower side. This is done in the PNP-500 concept hy suspending the reflector blocks on the top thermal shield, which is suspended on the PCRV top cap via elongations of the refueling penetration tubes. In a structure like this, the mass streams in the core cavity and hence the temperatures adjacent to the PCRV top cap strongly depend on the question at which time and in which way the components mentioned will fail. Therefore, this had to be studied before investigating the progressive failure of the top cap itself.

3.2 Failure of the top reflector

The top reflector consists of hexagonal graphite columns, which are subdivided in three layers of blocks. Each group of three graphite columns is combined forming a bearing unit, which is fixed to the top thermal shield by a suspension system, see Fig. 4. Failure of the top reflector is solely defined by exceeding of the strength of the steel used (decreasing with increasing temperature) by the stress due to dead load of the reflector at the weakest point of the structure. In order to find out this point, stresses in critical sections of the five elements marked in Fig. 4 were calculated. The result was that at first the mandrel (4) will fail, as soon as steel strength is decreased down to 5 % of the original strength. According to the material data at hand, this occurs at a temperature ϑ = 755 °C, which is reached in the central region at the time of 4.3 h. The lower hlock layers will glide down then and settle down onto the pebble bed. The upper layers, however, will be caught by the circular bearing plate and not glide down till the main suspension rod (5) is failing after 9.9 h. Towards the edge of the top reflector, the times of failure will be postponed due to the lower temperatures until about 17 h for the mandrel and about 44 h for the main suspension rod.

Because this kind of failure does not yield any change of mass streams in the cavities and because the reflector fails earlier than the top thermal shield (the latter being to some degree unloaded by failing of the reflector), the investigations for the thermal shield described below could be done without modifying the temperature transients used so far, which are valid for the completely intact core structure.

3.3 Failure of top thermal shield

The top thermal shield consists of 300 mm thick plates made of cast iron with spheroidal graphite GGG 40, the plates in the central region having hexagonal shape. Each of the plates is concentricly fixed by necked-down bolts to the flange at the end of the elongated penetration lining for a refueling tube, see Fig. 5. Investigations in order to find out the failure mode, showed that falling down of the shield plates is caused by exceeding of strength in the extension shank of the screws. This occurs at a temperature of 900 °C.

As shown in Fig. 6, temperatures of the accident sequence without depressurization and operating liner cooling - taken as a basis so far - will stabilize after initially increasing rather rapidly between 800 °C and 850 °C in the space between top thermal shield and PCRV top cap. Thus, the thermal shield would not fail in this case, and consequently also the PCRV would remain intact. If, on the other hand, the vessel is depressurized and liner cooling is out of operation, temperatures at first will increase slower, later on, however, elevating up to higher values than in the former case resulting in thermal shield failure after 170 h. From this time on, the PCRV insulation is exposed to hot gas of about 1200 °C. This leads to progressive degradation of the vessel top cap, which is described in the following section.

3.4 Progressive degradation of the PCRV top cap

As before in case of the HTR-1160, one of the penetrations arranged in equal distances together with the surrounding concrete (Fig. 7) is investigated taking advantage of the existing symmetry conditions. Up to the lower edge of the lower inside enlargement, there is a gap between the tube and the inside assemblies, so that the penetration surface here is directly exposed to the cooling gas. Failure is determined for steels at 1000 °C, for concrete at 800 °C, without regarding stress. Concrete in the region of reinforcement remains in place until the reinforcement is heated up to 1000 °C.

Fig. 8 shows a number of states of the progressive degradation, starting from operational condition (Fig. 8a). Fig. 8b presents the state immediately before failure of the thermal shield. Insulation and liner are still intact. Concrete - if locally already failed, especially outside the lowest reinforcement layer - remains still in place. After the top thermal shield has failed at t = 170 h, so that the hot gas of 1200 °C is directly acting on the PCRV top head, failure of insulation and liner occurs during a few minutes. One hour later, as much concrete as shown in Fig. 8c is already spalled. After 190 h, the failure front has reached the lower bound of the second concreting section, which is unreinforced in its lower part over 0.6 m height. Spalling of the unreinforced part is now taking place during about 23 hours, i.e. until t = 213 h. The state at the end of this period keeps unchanged until the end of the period of time analysed (Fig. 8d), since the following reinforced concrete does not fail at 800 °C, but only at 1000 °C as explained above. Thus, as a result, concrete is spalled during 250 hours up to a depth of 1.50 m.

3.5 Comparison with the HTR-1160 results

When comparing this result with that one of the HTR-1160 (see section 2.1), it is surprising that in spite of the more moderate initial temperature increase, the depth of the spalled layers as a wohle is 2.4 times greater. For this fact there are several reasons:

- The stand pipes are arranged closer than those of the HTR-1160; so, the mean temperature conductivity is more than 100 % higher.
- Contrary to the HTR-1160, the cooling gas is acting onto the structure without insulation up to a depth of 0.42 m.
- The heat withdrawal due to decarbonation of the limestone is missing in case of the PNP-500, because a basaltic concrete is provided.
- Under high temperatures, the thermal capacity of the basaltic concrete is lower than in the case of the limestone concrete chosen for the HTR-1160.

With the help of further failure calculations for the side wall, finally, the altogether spalled concrete masses were evaluated in dependence of time. Fig. 9 outlines the results. As shown in the graph, the total masses of concrete spalled in the top cap region are equal for PNP-500 and HTR-1160, although the spalling depths are so much different and the inside diameters are equal. This can be explained by the smaller volume of the concrete between the penetrations in case of PNP-500. At the side walls, however, the masses of spalled concrete depend more directly on the depth of failure. For further comparison, the masses of spalled concrete according to /4/ are plotted, which had been evaluated for the HTR-1160 by simplified methods. The significantly more advantageous result gained by more accurate analysis is obvious.

4. Conclusions

Considered by itself, the investigations described of course do not give complete information about the accident scenario and its consequences. Nevertheless, they demonstrate that this topic, which is important for the final result, has been treated conservatively within the risk analyses mentioned; that means by carrying out more accurate calculations in this field, one would have gained even more satisfactory overall results. In addition, these investigations demonstrate that structural details - like the shape of the connection between liner and stand pipes - and choice of concrete mix also with regard of its behaviour under high temperatures may be of great importance for the response of a PCRV on extremely high core temperatures and, thus, for the risk of an HTR plant. Last not least, these results show what a high temperature loading a PCRV is able to resist over a number of days without structural failure.

References

/1/ ALTES, J., SCHNEIDER, U., SCHIMMELPFENNIG, K., "Behaviour of a Prestressed Reactor Pressure Vessel for HTR Under High Core Temperature Loading", Transactions of the 6th Intl. Conference on SMiRT, Paris, France, August 17-21, 1981, Paper H 2/5.

/2/ General Atomic Company, "HTGR Accident Initiation and Progression Analysis", Status Report for US Department of Energy, GA-A 13617, 1976/77.

/3/ General Atomic Company, "HTGR Accident Initiation and Progression Analysis Phase II", Status Report for US Department of Energy, GA-A 15000, 1978.

/4/ Kernforschungsanlage Jülich GmbH, Institut für Nukleare Sicherheitsforschung, und Gesellschaft für Reaktorsicherheit mbH, "Sicherheitsstudie für HTR-Konzepte unter deutschen Standortbedingungen, Hauptband zur Phase Ib", Jül-Spez-136/Bd. 1, Jülich, Dezember 1981.

/5/ SCHIMMELPFENNIG, K., "Untersuchungen zum Verhalten eines HTR-Spannbetonbehälters bei extremen Core-Temperaturen", Konstruktiver Ingenieurbau - Berichte, Heft 38/39, Vulkan-Verlag, Essen, 1981, S. 88 - 96.

/6/ ABDUL-WAHAB, H.M.S., "The Rigidity of Perforated Plates with Reinforced Holes", Nucl. Eng. and Design, North-Holland Publishing Company, Amsterdam, 5 (1967).

/7/ SCHNEIDER, U., DIEDERICHS, U., EHM, C., "Effect of Temperature on Steel and Concrete for PCRV's", Nucl. Eng. and Design, North-Holland Publishing Company, Amsterdam, 67 (1981).

/8/ SCHNEIDER, U., DIEDERICHS, U., ROSENBERGER, W., WEISS, R., "Hochtemperaturverhalten von Festbeton", Sonderforschungsbereich 148, Brandverhalten von Bauteilen, Teilprojekt B3, Arbeitsbericht 1978 - 1980, Teil II, Technische Universität Braunschweig, Juni 1980.

/9/ ZERNA, W., "Die Dynamische Relaxation und ihre Anwendung auf Spannbeton-Reaktordruckbehälter", Deutscher Ausschuß für Stahlbeton, Heft 272, W. Ernst & Sohn, Berlin, 1976.

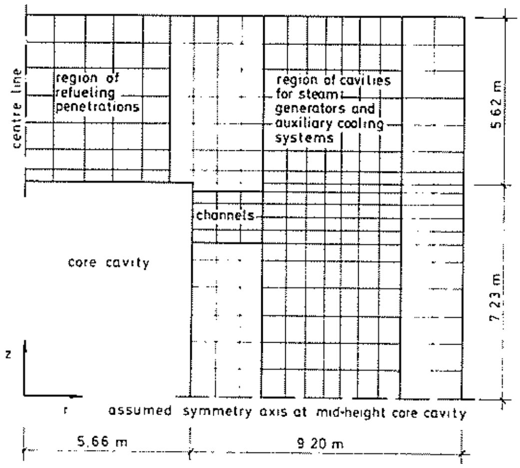

Fig. 1 Axisymmetric computation model for the upper half of the HTR-1160 PCRV

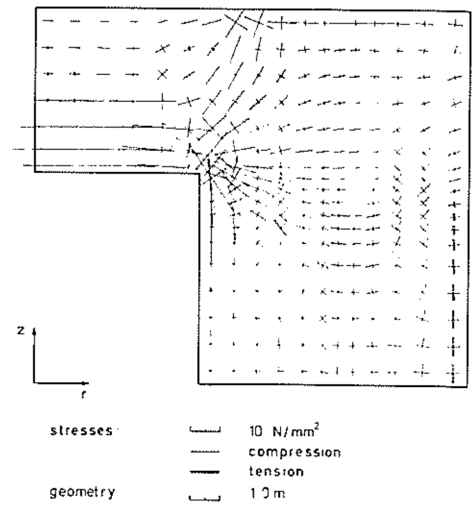

Fig. 2 Accident condition after 95 h time (at the end of vessel life), principal stresses in r-z-planes

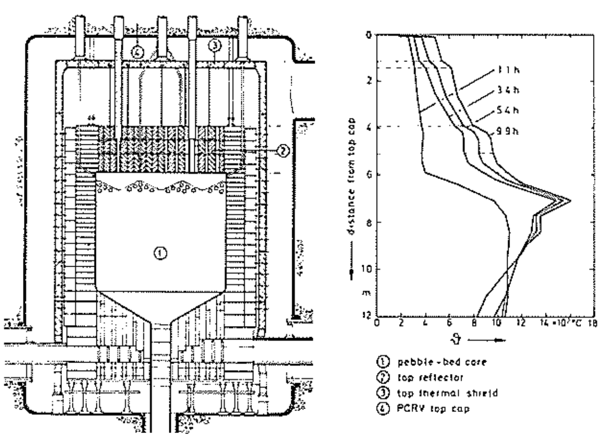

Fig. 3 Core cavity assemblies of the PNP-500 PCRV and accident temperatures at the cavity centre line

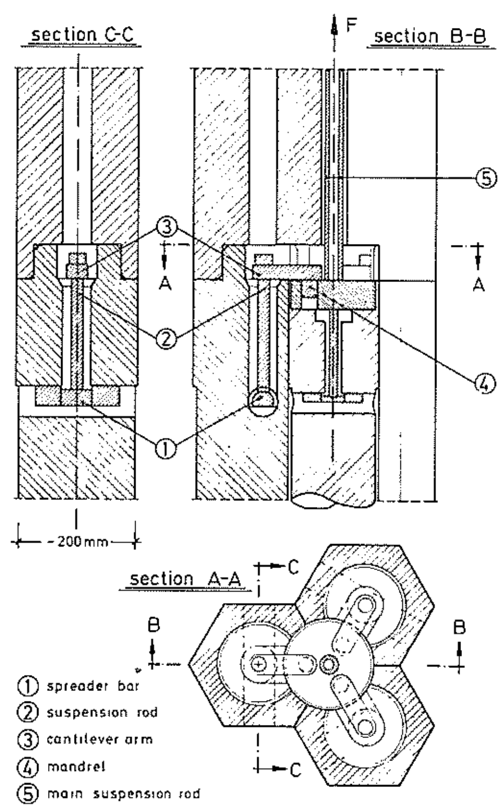

Fig. 4 Principle of the suspension device for the top reflector

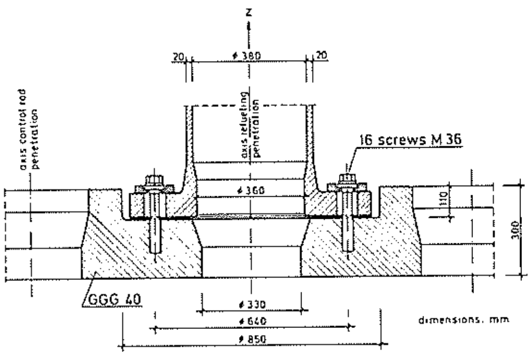

Fig. 5 Suspension of the top thermal shield

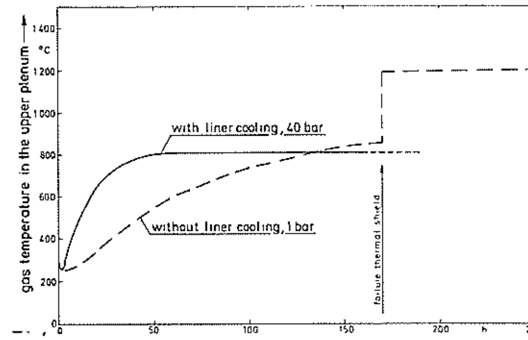

Fig. 6 Accident temperatures versus time
in the space between top cap and top thermal shield
for different accident conditions

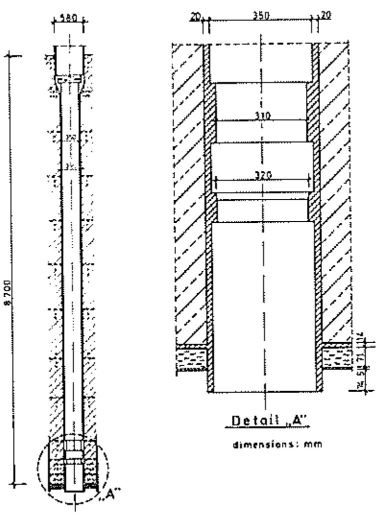

Fig. 7 Control rod penetration of the PNP-500 PCRV

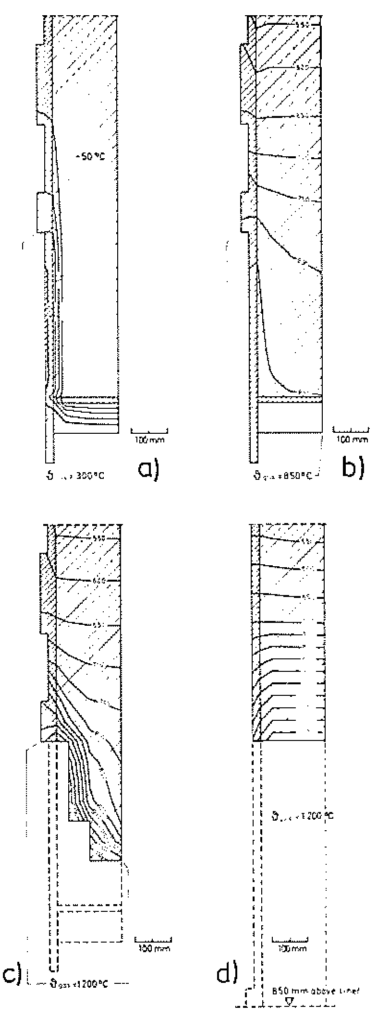

Fig. 8 Temperatures in the lower part of the PNP-500 top cap
a) stationary service conditions
b) 170 h after initiation of accident
c) 171 h after initiation of accident
d) 250 h after initiation of accident

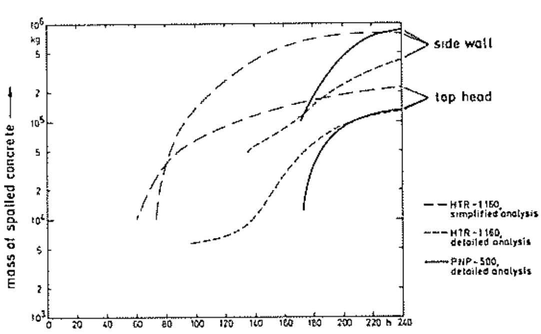

Fig. 9 Top head and side wall masses
of spalled concrete in different cases