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Safety Characteristics of the Circular and Annular Pebble-Cores for a 200MWth Prototype VHTR for a Hydrogen Production

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1. Introduction

Korea Atomic Energy Research Institute (KAERI) has proposed the conceptual design of a very high temperature gas-cooled reactor (VHTR) of a pebble-bed type with 200MW$_{th}$ (PBR200) for demonstrating a nuclear hydrogen production. The PBR200 is a simple and inherently safe nuclear system. The only safety-related system of the PBR200 is an air-cooled reactor cavity cooling system (RCCS) which has a capability of removing decay heat by cooling the reactor pressure vessel (RPV) wall with a natural circulation of air. Two types of pebble-bed cores are considered: annular core with a central reflector and a circular core. Since the safety characteristics during an accident strongly depend on the reactor core shape, fuel temperature behaviors of both pebble-core candidates are investigated for the limiting Low-Pressure Conduction Cooldown (LPCC) accident. The annular core with a large heat storage capability of a central reflector might be expected to have a large enough temperature margin for the fuel failure limit, but it is doubtful whether the circular core may have enough safety margin or not. In particular, since the thermal conductivity and heat capacity of the graphite pebbles and reflectors are a strong function of a fast neutron irradiation level, its impact on the degree of a safety margin is examined and discussed for both PBR200 candidates.

2. Design Parameters & Modeling Assumptions

The reactor core of PBR200[1] contains about 226,000 fuel spheres or "pebbles." The pebble is a sphere ball of 6cm in diameter, and each pebble contains nominally 15,000 UO_2 TRISO coated micro-spheres imbedded in a graphite matrix. Each pebble contains 9g of U, and fuel enrichment is 9.76w/o. Table 1 shows the major core parameters for PBMR[2] and two 200MWth PBR candidates. The annular core has the average power density of the core of 4.79 W/cc and the inner/outer radii of the active core, 80 and 147cm, respectively. The circular core has a lower average power density of the core of 3.56 W/cc, consistent with a large core volume. Both candidate cores have the same active core height of 8.73m and the same thickness of outer graphite reflector of 90cm.

Table 1 Core deign parameters for PBR200 Candidates

Design Parameter	PBMR 400MW	PBR200 CD 1	PBR200 CD 2
Thermal power (MW)	400	200	200
Inlet/outlet helium temperature (℃)	500/900	490/950	490/950
Active core inner/outer radius (cm)	100/185	80/147	0/143.18
Thickness of outer reflector (cm)	90	90	90
Effective core height (cm)	1100	873	873
Average power density (W/cc)	4.78	4.79	3.557
U235 enrichment for equilibrium fuel (w/o)	9.76	9.76	9.76

The candidate operating conditions are: helium inlet/outlet temperatures of 490/950°C, system pressure of 70bar, and helium flow rate of 83.2 kg/s. Main coolant flows into the lower reactor vessel and flows up to the upper plenum region through the riser channels inside a side reflector. Then, the coolant flows down through the pebble core and bottom reflector. Some bypass channels through the reactivity control system (RCS) hole for a control rod insertion and helium gap between the walls are also considered. No additional vessel cooling system is considered because modified 9Cr-Mo, of which the design limit for a steady operation is 495℃, is selected for the candidate material of the RPV. The GAMMA multi-dimensional

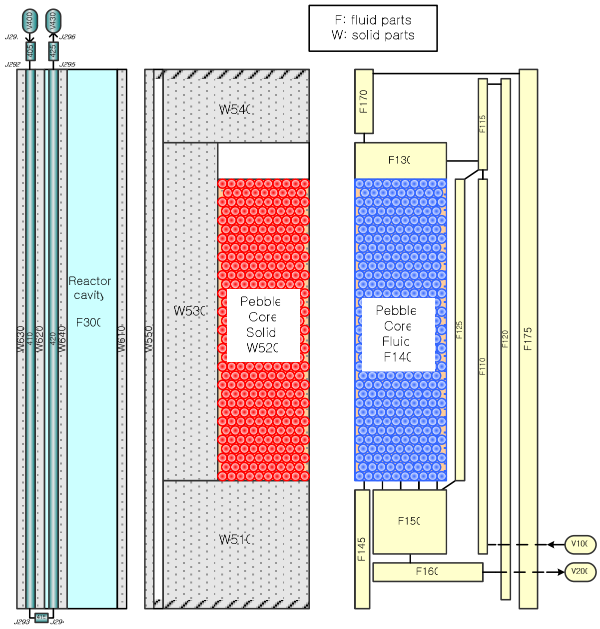

Figure 1. GAMMA System diagram for PBR200 CD2

analysis code[3] is used to model the PBR200 candidates. Overall system diagram of the PBR200 CD2 for the analysis is shown Fig. 1.

We choose the low pressure conduction cooldown (LPCC) event as the limiting accident in order to investigate the safety characteristics of the PBR200 candidates, because the fuel temperature reaches the highest among the Design Basis Accidents. The LPCC accident is initiated by a loss of coolant caused by a break of connection pipes. Immediately following the break, the coolant is discharged to an outlet boundary of an atmospheric pressure and the reactor power drops to a decay heat level. After the accident, the core decay heat and stored heat in the reflectors are transported by a heat conduction and radiation to the RCCS and eventually removed by the RCCS natural circulation cooling. The heat conduction through the core strongly depends on the irradiated condition because the heat capacity and thermal conductivity of the graphite pebble and reflector decrease as the irradiation level increases. In the analysis, we assumed an uniform irradiation dose of about 2.5 dosis (1 dosis=10^{21} fast neutrons/cm^2)

3. Results and Discussions

Following the LPCC accident, the fuel temperature starts to increase until the core residual heat balances the heat removal by the RCCS. After that, as the heat removal by the RCCS natural circulation cooling overcomes the core residual heat, fuel temperature continues to decrease slowly. As shown in Fig. 2, an increase of the fuel temperature is very slow for the annular-core PBR200 because the central reflector acts as a heat absorber with large heat capacity. Even with the examined irradiation level, the annular-core PBR200 has a large safety margin for the fuel failure limit (1600^{o}C). The circular-core PBR200 without a central reflector experiences a rapid increase in temperature following the accident. Under the examined irradiation level, the maximum fuel temperature reaches 1638^{o}C.

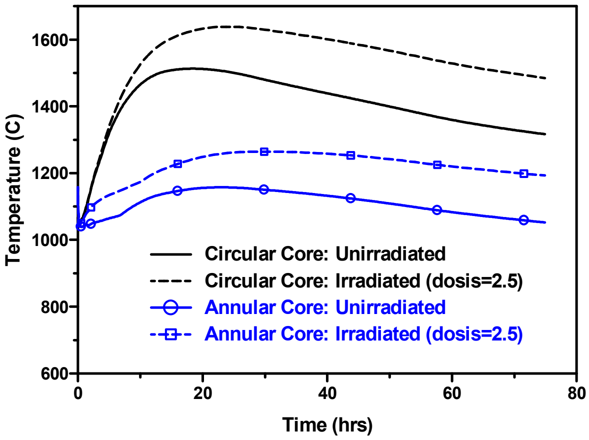

Figure 2. Maximum fuel temperatures during the LPCC accident

In order to attain an enough safety margin for the circular-core PBR200, two alternative approaches are suggested. First, the irradiation condition of a core graphite material is spatial-dependent due to the non-uniformity of fast neutron flux as well as time-dependent due to the accumulated damage of graphite during residence in the core. Therefore more detailed calculations on the core refuelling cycle and the lifetime of the graphite reflectors dependent on a fast neutron flux should be performed. Second, a slender core has a more surface area-to-volume ratio, by increasing the radiation heat transfer on the outside surface of the reactor pressure vessel.

4. Conclusions

From the assessment of the safety characteristics for two PBR200 candidates for a hydrogen production in a VHTR, it is found that the annular-core candidate for PBR200 has enough safety margins. It comes from the fact the central reflector plays an important role as a heat absorber in reducing the maximum fuel temperature during the accident. The effect of an irradiation on the thermal properties of the graphite pebble and reflector is the most important parameter to determine the fuel safety margin. The circular-core candidate for PBR200 has no fuel safety margin for the examined irradiated condition. Although the circular-core PBR has a lesser fuel safety margin, this option is more attractive in view of its simple design and easy maintenance. In order to attain a sufficient safety margin for the circular-core PBR200, further investigation is necessary for a re-shaped core dimension with a taller core or the use of a well-defined spatially-distributed irradiation level.

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