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Design concept for a small pebble bed reactor with ROX fuel

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ABSTRACT

The conceptual design of a small rock-like oxide fuel pebble bed reactor with once-though-then-out (OTTO) cycle is proposed here. TRISO-coated particles based on AGR-1 design were used to achieve a target burnup larger than 100 GWd/t-HM without any failure of spent fuel. In the first step, optimization of fuel composition was implemented by cell calculations. After that, whole core calculations were performed with and without movement of the fuel pebbles. With a heavy metal amount of 2 g per pebble and 20% uranium enrichment, the pebble bed reactor with OTTO cycle could achieve maximum burnup of about 145 GWd/t-HM and fissions per initial fissile atom (FIFA) of 75%. The results show that the core height can be reduced due to the fact that the impact of bottom core on burnup performance is insignificant. Also, the peak power density of the reactor exceeded the limit of that for the PBMR design. Therefore, subsequent optimizations of the core design were carried out by decreasing the core height and reactor power to reduce the construction cost as well as the peak power density. A reactor with 6-m core height and 120-MW_{th} reactor power was ultimately determined as the optimal design for a pebble bed reactor with ROX fuel. This optimal design also has a negative temperature coefficient, and the peak power density was less than the limit of 10 W/cm^3.

1. Introduction

Nuclear energy has been expected to play an important role in the future energy supply; however, it has to meet today's higher safety standards. The pebble bed reactor (PBR), a kind of high-temperature gas-cooled reactor (HTGR), is one of the most promising reactors in the generation IV initiative. This type of reactor is claimed to be have excellent passive safety features because of its graphite-moderated, helium-cooled and tristructural-isotropic (TRISO) fuel particles (Kadak, 2005). Rock-like oxide (ROX) fuel has been studied at the Japan Atomic Energy Agency (JAEA) as a new once-through type fuel concept. With both mineral and ceramic properties, it is desired to improve the performance of the fuel elements not only in normal operation, but also for geological disposal without further reprocessing (Akie et al., 1994; Kuramoto et al., 2003; Nitani et al., 2008).

Previous studies have been performed to access the potential of using ROX fuel in HTGRs. A clean burn high temperature gas-cooled reactor (CBHTR) that uses PuO_2-YSZ fuel and thereby recovers spent Pu fuel from light water reactors has been under development at JAEA (Minoru, 2013). Other research (Ho and Obara, 2015) showed that UO_2-YSZ fuel can be used in small PBRs with high-discharge burnup even if the fissile density is five times lower than that of conventional UO_2 fuel. The UO_2-YSZ fuel also presents an advantage in comparison with the UO_2 fuel as it has higher stability in the geological disposal of spent fuel without significantly reducing burnup performance. However, the previous study only showed the possibility of using ROX fuel in once-through-then-out (OTTO) cycle pebble bed reactor; optimization for burnup performance was not performed.

The purpose of this study was to introduce the design concept for a small PBR with ROX fuel and to optimize the ROX fuel composition so that the reactor can achieve as high a burnup as possible without any failure of the spent fuel in the OTTO cycle. The power peak was set to less than the limit of the reference PBMR design to ensure that the reactor can be cooled by natural circulation and still survive in accident scenarios. In addition, an analysis of temperature coefficients was carried out to show the negative reactivity coefficient of the PBR with the UO_2-YSZ fuel.

2. Optimization of fuel composition by cell calculations

2.1. Fuel design

To satisfy the high burnup in a once-though fuel cycle, the PBR with ROX fuel should utilize the fuel designs that have been successful in high burnup irradiation tests. It was found that the

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AGR-1 (Maki, 2009) could achieve a high burnup without any observable failures up to approximately 200 GWd/t-HM. Therefore, this study used the AGR-1 fuel design for the calculations. The main parameters of the fuel pebbles and AGR-1 TRISO particles are presented in Table 1. This study utilized low-enriched uranium with a maximum 20% concentration of $_{235}$U. A single-phase UO_2-YSZ fuel, consisting of 81.75 mol% YSZ (78.6 mol% ZrO_2 + 21.4 mol% $YO_{1.5}$) and 18.25 mol% UO_2, was used as the fuel in the kernel, as in the previous study (Ho and Obara, 2015).

2.2. Methodology

In the first step, cell calculations were implemented to estimate the optimal fuel composition that could be applied for further analyses in a PBR with the same fuel design as mentioned above. Random parking (RP) with a packing fraction of approximately 61% was chosen to distribute the fuel pebbles in the cell geometry. The cell geometry was surrounded by a reflective boundary condition. In order to determine the optimal fuel composition, the amount of heavy metal in each pebble (HM loading) and the enrichment of uranium were changed. The HM loading can be adjusted by changing the number of TRISO particles in the graphite matrix of the fuel pebble: the more TRISO particles, the greater the HM loading, with 4.5 g being the maximum HM loading for the ROX fuel, corresponding to a TRISO-coated fuel particle (CFP) volume-packing fraction of 40%. Criticality analyses were performed using a continuous-energy Monte Carlo code, namely MVP-BURN (Okumura et al., 2006), and the JENDL-4.0 nuclear data library (Shibata et al., 2011).

2.3. Results

The change of the infinite multiplication factor (k_∞) as a function of operation time in the case of 3-g HM loading with different uranium enrichments is shown in Fig. 1. It can be seen that higher uranium enrichment made k_∞ decrease to unity more slowly, and as a result the operation time could be longer.

Figs. 2 and 3 illustrate the burnup and FIFA, respectively, as a function of HM loading and uranium enrichment when the k_∞ became unity in cell calculations. According to Fig. 2, the burnup decreased with decreasing uranium enrichment at the same amount of HM loading. The case of 3-g HM loading with 20% uranium enrichment gave the highest burnup of about 135 GWd/t-HM when k_∞ equaled one. As can be seen in Fig. 3, the FIFA was almost the same at the same amount of HM loading even if the enrichment of uranium was changed from 12% to 20%. However, the FIFA was reduced from about 75% to 65% when the amount HM loading increased from 1.5 to 4.5 g. This is because the moderator-to-fuel-volume ratio decreased when the amount of HM loading increased from 1.5 to 4.5 g. Decreasing the moderator-to-fuel-volume ratio made the neutron spectrum shift to being harder.

Table 1
Fuel designs.

Properties	Unit	Value
Fuel pebble		
Pebble radius	cm	3.0
Thickness of fuel-free zone	cm	0.5
Density of carbon matrix	g/cm^3	1.74
Coated particles		
Kernel diameter	μm	350
Kernel density	g/cm^3	6.55
Coating materials	–	C/C/SiC/C
Layer thicknesses	μm	100/40/35/40
Layer densities	g/cm^3	1.10/1.85/3.20/1.85

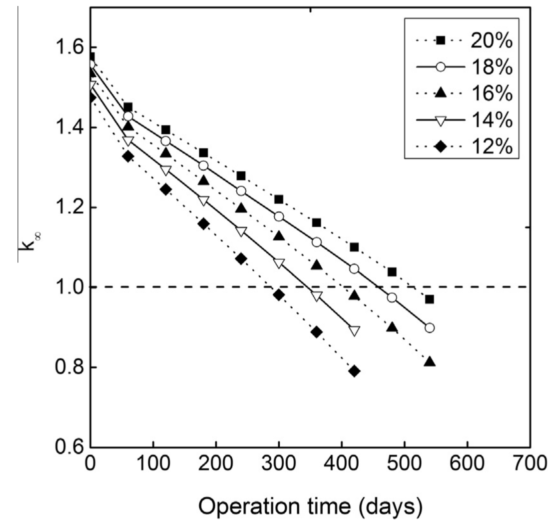

Fig. 1. Change of k_∞ in cell calculations for different enrichment in the case of 3-g HM loading.

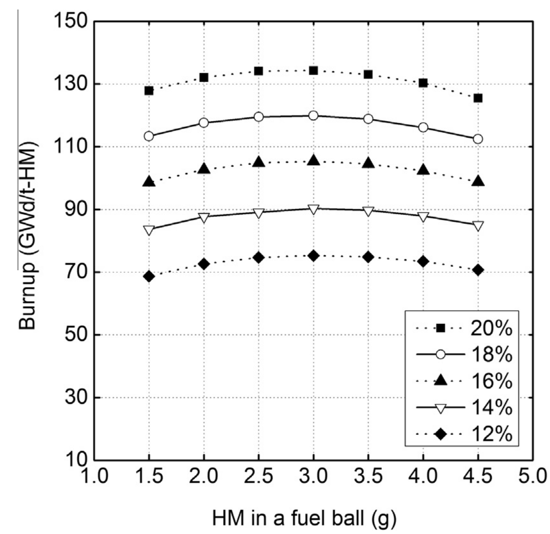

Fig. 2. Burnup in cell calculations for different enrichments and HM-loading schemes.

This made the fuel burnup less effective by increasing the amount of HM loading.

The results at critical state showed that 20% of enriched uranium and about 2.5–3 g of HM loading was the optimal fuel composition in cell calculations, at which the burnup and FIFA could reach their highest values. Therefore, this composition will be used as a reference design for subsequent analyses in this study.

3. Optimization of fuel composition in a small PBR without movement of fuel pebbles

In the actual reactor, the neutron leakage is very complicated due to the existence of the graphite reflector. Chapter 2 performed the burnup calculation of the fuel with the reflective boundary condition. It is difficult to determine the buckling properly without taking into account the neutron leakage. Therefore, this chapter carried out the burnup performance by whole core calculations with graphite reflector to estimate more properly neutron leakage effects. In the analysis, it is assumed that there was no movement of fuel pebbles in the core during operation.