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Flattening of burnup reactivity in long-life prismatic HTGR by particle type burnable poisons

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ABSTRACT

For the flattening of burnup reactivity in long-life prismatic High-Temperature Gas-cooled Reactors (HTGRs), the effect of particle type on burnable poison properties is analyzed in detail using Monte Carlo calculations. Some examples of optimized specifications are shown. It is shown that combinations of particles with different materials, diameters, and concentrations make it possible to reduce excess reactivity to around or below 1 $ during the core life. The use of optimized burnable poison particles will help improve the passive safety features of long-life prismatic HTGR.

1. Introduction

High-Temperature Gas-cooled Reactors (HTGRs) are especially attractive from the viewpoint of their excellent passive features in case of accidents, namely, the large heat capacity of the graphite core and their capacity for passive cooling by radiation and natural circulation. A small and passive-safe HTGR can be an attractive reactor for use in remote areas or small islands if it has long-life core. In the design of long-life small prismatic HTGRs, it is necessary to use highly enriched uranium to increase the fissile inventory. At the same time, it is necessary to load an effective burnable poison (BP) to compensate for excess reactivity during the core life. It is important to plan for a flat reactivity curve over time, or to minimize excess reactivity during the core life in order to minimize the insertion of control rods during operation, in large part to avoid damage to the rods by high temperatures. In addition, a surge of positive reactivity can occur upon the withdrawal of control rods, which can lead to severe accidents. Termination of such severe accidents by passive safety features alone is very difficult. Thus, minimizing excess reactivity during operation by optimization of BP is important.

Various studies have been performed on particle-type BPs. Two major parameters influence the reactivity control of BP particles: namely the diameter of particle and the number density in the fuel element. Theoretical studies of BP particles in HTGRs have been performed (Hugo, 2000; Talamo, 2006, 2010) and a study to reduce reactivity swing using single BP particles has been performed (Kloosterman et al., 2003). A study on employing BP particles to reduce power peaking in pebble bed reactors has also been performed (Tran et al., 2008). With further optimization, BP particles have the possibility to reduce the maximum excess reactivity in the long-life operation of an HTGR. In particular, the use of two types of particles expands the options for optimization. There are two ideas for using two types of particles: one is to use the same BP material with different diameters and number densities, the other is to use two different BP materials with different diameters and number densities.

In the case of a reactivity insertion accident, withdrawal of only a single rod is usually considered. If it is possible to reduce the maximum excess reactivity to less than 1 $ by the use of an optimized BP particle combination, the excursion of reactor power can be very moderate even if all of control rods are withdrawn during the operation. Optimization of BP composition can markedly increase the passive safety features of an HTGR.

The purpose of this study was to show that it is possible to use BP particles to reduce the excess reactivity in long-life HTGR and thereby avoid prompt critical accidents. Especially, the effect of the use of two types of BP particles to flatten the reactivity curve is considered.

2. Effect on burnup reactivity of single-material BP particles

The effect on burnup reactivity of single-material BP particles was investigated first. Several materials were tested for use in BP

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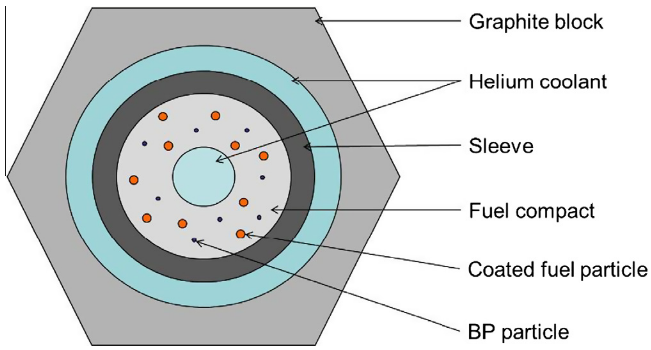

Fig. 1. Geometry for single cell analysis.

particles. Analyses were performed changing the diameter and the number density of the particles.

Numerical analysis was performed for an infinite single-cell model. Fig. 1 shows the geometry of the analysis, which is based on the design in HTTR (Saito et al., 1994). The BP particles are mixed with coated fuel particles (CFPs) in the region of the fuel compact. The major specifications of the fuel element are shown in Table 1. The volume packing fraction of CFPs in the fuel compact was set to 6.6%. The volume ratio was decided by the ratio of moderator to fuel in the whole-core model. The packing fraction in the fuel compact is lower than the normal value, but the ratio of moderator to fuel in whole core is the same as that when the packing fraction is set to 30% in the whole-core model. This study aimed to flatten the reactivity swing in a long-life HTGR. The enrichment of uranium was set to 20%.

Numerical analysis was performed using continuous-energy Monte Carlo code MVP2.0 (Nagaya et al., 2005) and MVP-BURN (Okumura et al., 2000) with nuclear data library JENDL-4.0 (Shibata et al., 2011). The MVP2.0 code has a function that treats the double heterogeneity of HTGR fuel elements by a Statistical Geometry Model (Nagaya et al., 2005). This function was used for the analysis.

Table 1
Major specifications of fuel elements and graphite block.

Graphite block	
Material	IG-110
Widths across flats	36 cm
Height	58 cm
Density	1.77 g/cm^3
Helium coolant channel	
Outer diameter	4.10 cm
Fuel rod	
Outer diameter	3.4 cm
Length	57.7 cm
Number of fuel compacts	14/rod
Fuel compact	
Outer diameter	2.6 cm
Inner diameter	1.0 cm
Length	3.9 cm
Packing fraction of CFPs	6.6 vol.%[a]/4.0 vol.%[b]/30 vol.%[c]
Fuel kernel	
Material	UO_2
Diameter	0.0597 cm
Enrichment	20 wt%
Density	10.4 g/cm^3
Coatings	
Materials	Buffer/PyC/SiC/PyC
Thickness	60/30/25/45 μm
Density	1.10/1.85/3.20/1.85 g/cm^3

[a] For cell calculations.
[b] For infinite fuel block calculations.
[c] For finite core calculations.

Table 2
Major properties of burnable poison materials.

BP materials	Main absorbing nuclides	Main absorber content (wt%)	Density (g/cm^3)
B_4C	^{10}B	90	2.52
Gd_2O_3	^{155}Gd, ^{157}Gd	14.8, 15.65	7.4
Er_2O_3	^{167}Er	22.95	8.64
CdO	^{113}Cd	12.22	8.15

The materials tested for BP particles were B_4C, Gd_2O_3, Er_2O_3 and CdO. The major parameters of the materials used in the analysis are shown in Table 2. A single material was used for BP particles and distributed uniformly in the fuel compact by changing the number of particles in the fuel compact and their diameter (d_{BP}). In the analysis, the concentration of BP particles in the fuel compact was shown by V_F/V_{BP}, which is the volume ratio of fuel to BP. Changes of the infinite multiplication factor (k_∞) were calculated during the burnup. The average power density in the burnup analysis was set to 2.5 W/cm^3, which was the value in HTTR. The temperature of all materials was set at 1200 K.

The analysis results showed that the diameter of BP particles had a lot of effect on the reactivity swing during the core life. If the diameter is small, the k_∞ at the beginning of the reactor life can be very small, but it increases rapidly and becomes almost the same reactivity in the case of having no BPs in the fuel compact. Fig. 2 shows an example of the effect in B_4C particles in various d_{BP} when V_F/V_{BP} is 50. If the d_{BP} is 0.010 cm, which is the smallest diameter in the analysis, the initial k_∞ can be very small but it rapidly increases and becomes almost the same as that in no BP case. The volume fraction of BP particles in the compact also had a great effect on the average k_∞ during the core life. Adjustment of V_F/V_{BP} is effective at keeping the reactor critical during the whole core life. Based on the observed effects, the optimum d_{BP} and V_F/V_{BP} were decided for each type of BP particle. For the optimization, the reactivity during the core life was defined as:

$$\Delta\rho_\infty = \frac{k_\infty - 1.1}{k_\infty}.$$

The purpose of analysis is to know the general characteristics using simple cell model. So the target k_∞ for the optimization was set to 1.1 tentatively in the definition. The reactivity was estimated after the xenon concentration became equilibrium.

The optimum parameters for each BP particle and the maximum reactivity during the core life are shown in Table 3. The change of k_∞ is shown in Fig. 3. The k_∞ values after the xenon concentration became equilibrium were used to discuss the reactivity. The maximum reactivity without burnable poison was about 31%. The use of BP particles has a significant effect on minimizing the excess reactivity. Using them the maximum reactivity can be about 7% or less. The optimized d_{BP} and V_F/V_{BP} are different for different materials, as expected. B_4C has the smallest $\Delta\rho_\infty$ during the core life, and the life is the longest if BP particles with small d_{BP} are used with large V_F/V_{BP} condition. Gd_2O_3 is the strongest absorber, so if the d_{BP} is small, the initial reactivity becomes too small and increases rapidly. By this effect, the d_{BP} must be large enough to flatten the reactivity swing during core life. This causes a larger self-shielding effect, so it is needed to make the V_F/V_{BP} smaller. Er_2O_3 is the weakest absorber among them, so the reactivity effect can be expected only when the V_F/V_{BP} is very small and the d_{BP} is also very small. A small d_{BP} results in a large depression of initial reactivity; thus, it can be difficult to make the reactivity almost constant for a long period. Another candidate for BP is CdO, whose