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Reevaluation of Burnable Poison Effects in a VHTR

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1. Introduction

For a safe and reliable operation of the block-type VHTR (Very High Temperature Reactors), a burnable poison (BP) is inevitable to reduce the burnup reactivity swing and to control the core power distribution. The objective of this work is to find a promising BP material and to optimize the BP design in terms of the core performances. A 600MWth VHTR core, which was modified from the GT-MHR[1] design, is considered for the neutronic study. A sintered mixture of BP and a carbon matrix[2] is adopted for the BP application since it provides a residual reactivity and is less costly, as compared with the coated particle type one. Our previous work[3] showed that B_4C provides a better performance than Er_2O_3, Gd_2O_3. In this work, a more comprehensive evaluation is implemented for more BP materials and a physics study is done to minimize the reactivity swing.

2. Description of Work

Figure 1 shows the 3-ring annular core model comprised of 108 fuel columns. Each fuel column is comprised of 9 fuel blocks, instead of 10 for the original design. The active core height is 7.93m and the core is reflected by 120cm-thick top/bottom graphite reflectors. The coolant inlet and outlet temperatures are 490°C and 950°C, respectively.

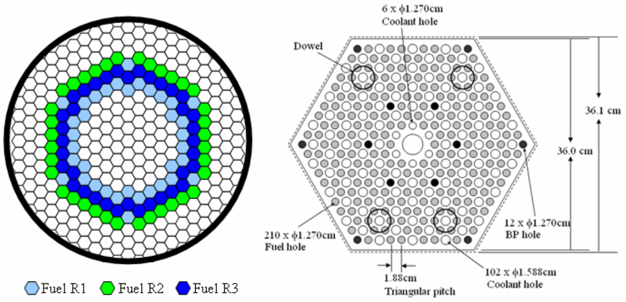

Fig. 1. Configuration of the core and fuel block.

We have considered two BP loading strategies, either 6 BP holes or 12 BP holes. In the case 6 BP holes, only the 6 holes located in the corners of the hexagon are used and the others are used as fuel holes. A conventional 3-batch radial shuffling is considered: the fresh fuel is loaded into the R2 region and moved subsequently into R3 and then R1. The fuel kernel is a UO_2 of a 12% uranium enrichment and the diameter of the kernel is 500μm. TRISO packing fraction is 27.5%. The coating thickness is as follows: 100μm for the buffer, 40μm for the inner and outer PyC, and 35μm for the SiC. Diameter of the standard BP compact is 0.6 cm.

A TH-coupled core analysis is implemented with the HELIOS[4]-MASTER[5] code system, in which a two-step modern diffusion nodal approach is used. The core performance is evaluated for an equilibrium cycle.

3. Evaluation of Burnable Poison Materials

For the reference block design with 6 BP holes, neutronic performances of 8 BP materials (B_4C, Er_2O_3, Gd_2O_3, Gd_2C_3, CdO, Eu_2O_3, Sm_2O_3, Dy_2O_3) have been evaluated. For a systematic comparison, BP loading was determined for the same target reactivity swing of ~5,000 pcm. Table I clearly shows that B_4C, Gd_2O_3, Gd_2C_3, and CdO BPs are rather promising in terms of the fuel burnup and CdO provides the biggest fuel burnup. For the three favorable BPs the core temperature coefficients were also comparable, although the Gd_2O_3 and Gd_2C_3 BPs resulted in less negative coefficients. Figure 2 shows the evolution of the equilibrium reactivity for the three BPs.

Table I. Comparison of various BP materials

BP type, volume fraction (%)	Cycle length, Day	Reactivity swing, pcm	Burnup, GWD/tU
No BP	477	15,087	103.7
B_4C, 1.82	405	4,865	88.0
Gd_2O_3, 3.75	432	5,280	93.9
Gd_2C_3, 3.40	430	5,183	93.4
Er_2O_3, 7.1	329	4,975	71.5
CdO, 6.68	467	5,231	101.5
Eu_2O_3, 0.9	311	4,710	67.6
Sm_2O_3, 1.77	374	5,076	81.3
Dy_2O_3, 2.50	245	7,292	53.2

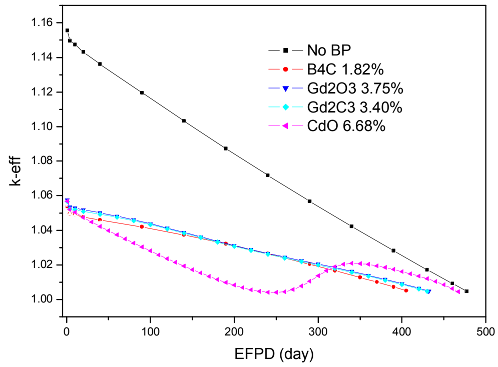

Fig. 2. Equilibrium cycle reactivity with 6 BP holes.

4. Impact of 12 BP holes

For a reduced burnup penalty in a BP, the self-shielding effect of a BP should be minimized and an effective way is to use 12 BP hole[3], i.e., dilution of BP density.

In order to further reduce the reactivity swing and burnup penalty of B_4C and Gd_2C_3, the BP was loaded into 12 BP holes. In this case, the total amount of BP is the same as in the previous 6-hole case. The fuel mass per block is 97.1% of the 6-hole BP case, due to the reduced number of fuel holes. Table II summarizes the results in terms of the cycle length, reactivity swing, and average discharge burnup. In Fig. 3, the equilibrium reactivity behavior is shown.

Table II. Performance with 12 BP holes

BP type, volume fraction (%)	Cycle length, Day	Reactivity swing, pcm	Burnup, GWD/tU
B_4C, 0.91 (radius=0.60 cm)*	417	3,197	93.3
Gd_2C_3, 1.70 (radius=0.60 cm)*	449	2,781	100.4
Gd_2C_3, 2.656 (radius=0.48 cm)*	448	2,429	100.2
Gd_2C_3, 3.469 (radius=0.42 cm)*	446	2,845	99.7

*Radius of BP compact

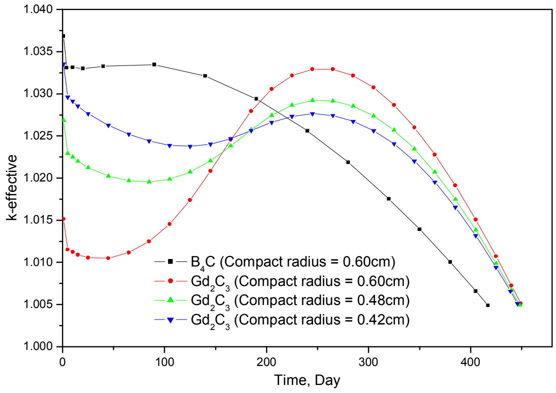

Fig. 3. Reactivity changes in equilibrium cycle (12 holes).

In the case of B4C, the cycle length and fuel burnup were increased by about 6.0% and the reactivity swing was also significantly reduced, although the same amount of BP was used. This is mainly due to the reduced self-shielding effect. Similar improvements were observed for the Gd_2C_3 BP loaded into the standard-size (radius=0.6 cm) BP hole. Meanwhile, Fig. 3 indicates that the core reactivity, in the case of Gd_2C_3, shows a very non-linear behavior: the excess reactivity near a BOC is very low and it increases rather fast in the middle of a burnup. Such unfavorable reactivity change is due to the large self-shielding in the gadolinia BP. In VHTRs, the core excess reactivity needs to be at least ~1500 pcm to compensate for the Xenon worth during a power maneuvering. For a slow reactivity change, the depletion rate of gadolinia needs to be reduced, i.e., the self-shielding should be increased. The self-shielding effect in a BP hole can be easily adjusted by changing the effective radius of the BP zone. As shown in Table II and Fig. 3, the reactivity change is quite flat with a compact radius of 0.42 cm at a cost of a slightly reduced fuel burnup.

5. Conclusions

In the typical block-type VHTR, B_4C, Gd_2C_3, and CdO are rather promising BP materials in terms of the fuel burnup and CdO shows the smallest burnup penalty. A 12-hole BP loading provides a better performance than the usual 6-hole BP application. For an optimal application of the B_4C BP, the self-shielding effect of a BP should be minimized. However, in the case Gd_2C_3, the BP self-shielding needs to be optimized for a favorable reactivity change. In spite of the excellent neutronic performance of CdO, its low boiling temperature (~1560 C) would be problematic in a VHTR. With a radial fuel block shuffling scheme as used here, the maximum fuel temperature can be increased significantly if the reactivity swing is reduced considerably. A design measure needs to be devised to minimize both the burnup swing and the fuel temperature simultaneously.

ACKNOWLEDGEMENTS

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