APPLICATION OF BURNABLE POISON PARTICLES FOR IMPROVING NEUTRONICS PERFORMANCE OF VVER-1000 FUEL ASSEMBLY

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Abstract: Application of Gd_2O_3 in form of burnable poison particles (BPPs) has been investigated for improving neutronics performance of VVER-1000 fuel assembly. Numerical calculations have been conducted for optimizing BPP parameters using the MVP code and the JENDL-3.3 data library. The results show that by using Gd_2O_3 particles with the diameter of 60 μm and the packing fraction of 5% the burnup reactivity curve and pin-wise power distribution are obtained approximately that of the reference design. To minimize power peaking factor (PPF), two models of assembly consisting of 18 BPP-dispersed rods have been selected so that the burnup reactivity curve is approximate that of the reference one, while the PPF decreases from 1.167 to 1.105 and 1.113, respectively.

Keywords: *VVER-1000 assembly, burnable poison, burnup reactivity, power peaking factor.*

1. INTRODUCTION

A typical VVER-1000 fuel assembly consists of 12 gadolinia bearing fuel rods for controlling nearly constant burnup reactivity from the beginning of burnup up to about 10 GWd/t. The disadvantage is that gadolinia has a smaller thermal conductivity compared to UO_2 fuel, resulting in a smaller thermal conductivity of gadolinia bearing fuel pellet [1]. Meanwhile, a high thermal conductivity of fuel pellet is desirable for future designs with high burnup and power density. One possible solution is using Gd_2O_3 in form of burnable poison particles (BPPs) distributed in UO_2 fuel matrix [2]. Experiments conducted by Iwasaki et al. found that by adding 10 wt% Gd_2O_3 in form of BPPs with the diameter of 25-53 μm the fuel pellet has the thermal conductivity of about 5.8-2.7 W/mK in the temperature range of 300-1273 K [3]. This value is greater than that of UO_2-Gd_2O_3 solid fuel (3.8 to 2.6 W/mK) [3]. This means that by using Gd_2O_3 in form of BPPs in the fuel pellet the thermal conductivity could be improved significantly.

In the present work, we summarize the investigation results obtained in a previous work and the recent extension on the use of BPPs for controlling burnup reactivity curve and improving the neutronnics performance of the VVER-1000 fuel assembly [4]. Spherical BPPs of Gd_2O_3 were distributed in UO_2 fuel. The BPP diameter and the packing fraction are optimized for obtaining a flat k_∞ curve at the beginning of burnup stage. The objective is to obtain the k_∞ curve similar to that of the reference assembly with homogeneous mixture of UO_2-Gd_2O_3. Then, the neutronics performance of the newly designed fuel assembly including pin-wise power distribution and PPF is evaluated and compared with that of the reference assembly. Investigation has also been performed to minimize the PPF by distributing the BP more uniformly in the assembly. Two models of fuel assembly with 18 fuel rods containing BPPs have been selected. The BPP parameters are then optimized for attaining similar burnup reactivity curve but smaller PPF compared to the reference design.

2. NEW DESIGNS OF VVER-1000 ASSEMBLY WITH BPPs

2. 1. Calculation model

Fig. 1 displayed the cross sectional view of the reference VVER-1000 fuel assembly [5]. The assembly consists of 300 UO_2 fuel rods and 12 gadolinia bearing rods as shown in Fig. 1. The ^{235}U enrichment is 3.7 wt% for the UO_2 fuel rod and is 3.6 wt% for gadolinia bearing rod, respectively. The detailed parameters of the VVER-1000 fuel assembly can be found in Ref. [5]. Numerical calculations have been carried out for designing new fuel assembly of the VVER-1000 reactor using the MVP code and the JENDL-3.3 library [6, 7]. The statistical geometry (STG) model of the MVP code was used to simulate the random distribution of BPPs. The number of histories is chosen as 25×10^6 so that the relative statistic error of the k_∞ less than 0.01% can be achieved.

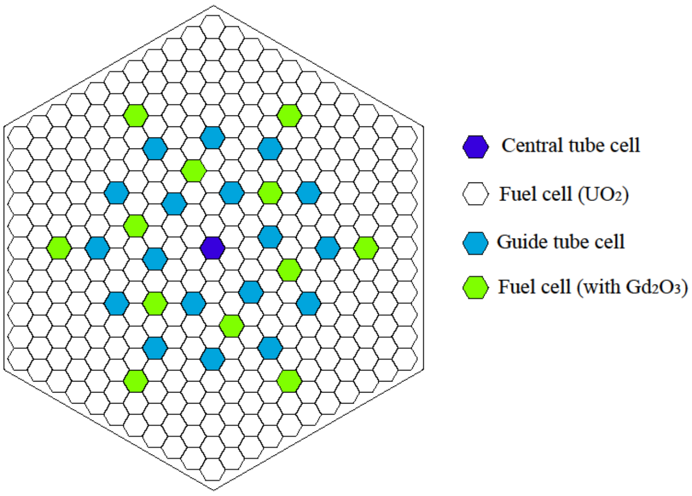

Fig. 1 Configuration of the reference VVER-1000 fuel assembly.

2. 2. Fuel assembly with 12 BPPs-dispersed fuel rods

In this work, we investigated the possibility of using BPPs of Gd_2O_3 for controlling the burnup reactivity curve and flattening the power distribution. The diameter and the packing fraction of Gd_2O_3 particles are determined so that the k_∞ curve of the new assembly is flattened similarly to that of the reference one. In the design procedure, it is assumed that the same content of Gd_2O_3 but in form of BPPs is added into the fuel pellet as in the reference design. A parametric survey has been carried out to determine the optimal diameter of the BPPs. Since the objective is to attain the k_∞ curve approximate the reference one, the diameter of 60 m was determined. The neutronics performance such as the k_∞ curve, pin-wise power distribution and PPF of the new fuel assembly is evaluated. Fig. 2 depicts the k_∞ curve of the new fuel assembly with the optimal BPP design (the diameter of 60 µm and the packing fraction of 5%). The k_∞ curve is approximate the reference one with homogeneous mixture of the same Gd_2O_3 amount.

Fig. 3 displays the PPF as a function of burnup of the new fuel assembly designed with Gd_2O_3 particles compared with that of the reference one. One can see that in the case of no gadolinia bearing rod, the PPF is about 1.04-1.07 during burnup from 0 to 40 GWd/t. In the reference assembly with homogeneous Gd_2O_3, the PPF is greater in the early burnup stage of 0-10 GWd/t. This burnup range also corresponds to the most effect of BP on the reactivity curve. The PPF decreases with the increase of burnup, and after 10 GWd/t the PPF is around the value of 1.04-1.06. By using the BPPs, the PPF decreases slightly by about 0.9% at the beginning of burnup. The merit obtained for the newly designed assembly is the higher thermal conductivity of the BBP-dispersed fuel pellet.

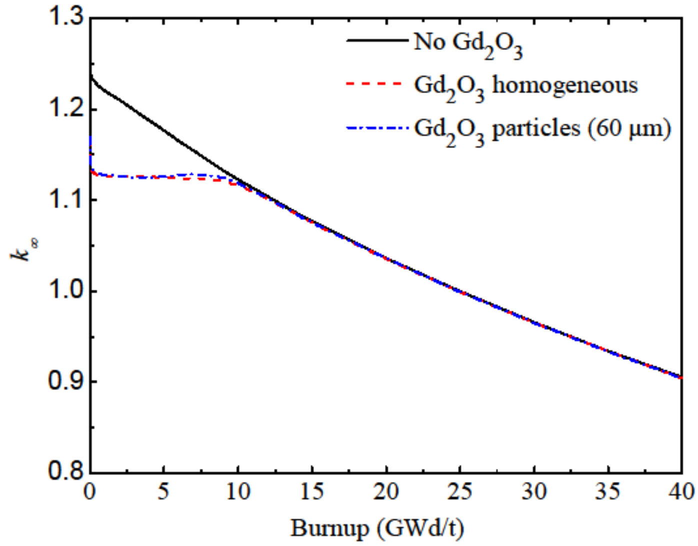

Fig. 2 The k_∞ curve of the VVER-1000 fuel assembly with 12 UO_2-Gd_2O_3 rods.

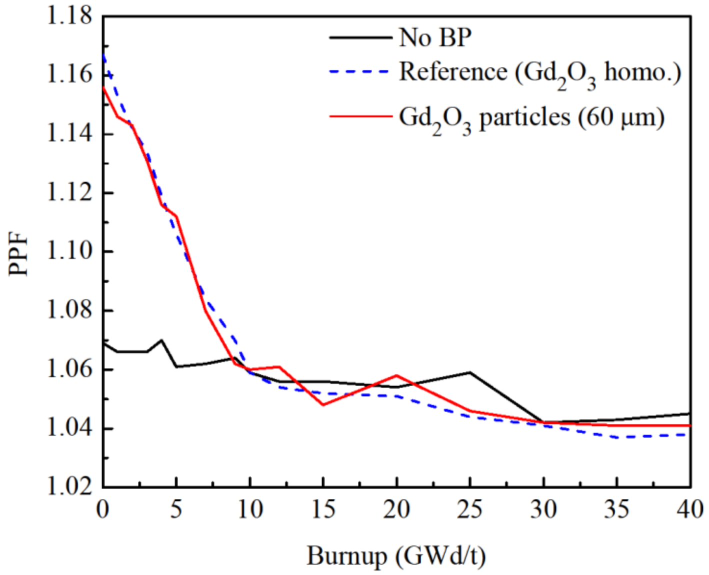

Fig. 3 PPF as a function of burnup of the VVER-1000 assembly with 12 UO_2-Gd_2O_3 rods.

2. 3. New assembly with 18 Gd rods

Investigation has also been carried out to improve the pin-wise power distribution and reduce the PPF at the beginning of burnup (0-10 GWd/t) by optimizing the number of Gd_2O_3-dispersed fuel rods and their positions in the fuel assembly. A survey of design has been conducted to determine the number of UO_2-Gd_2O_3 fuel rods and the positions in the assembly. As a result, two models of the assembly with 18 UO_2-Gd_2O_3 fuel rods has been selected corresponding to different arrangements of UO_2-Gd_2O_3 fuel rods in the assembly. Fig. 4 displays the two configurations of the new assembly designed with 18 BPP-dispersed fuel rods.

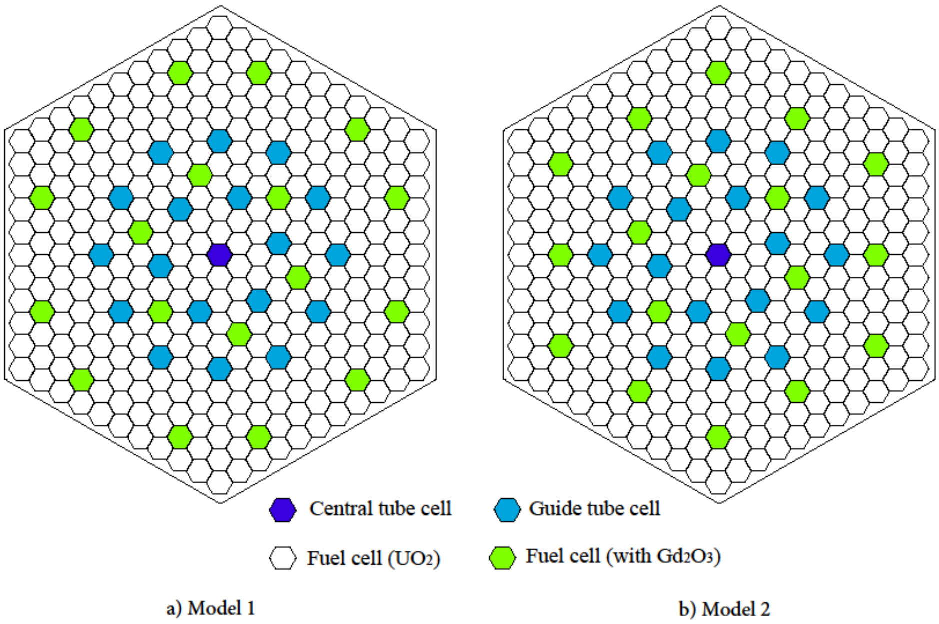

Fig. 4 Configurations of the VVER-1000 fuel assembly with 18 UO_2-Gd_2O_3 rods.

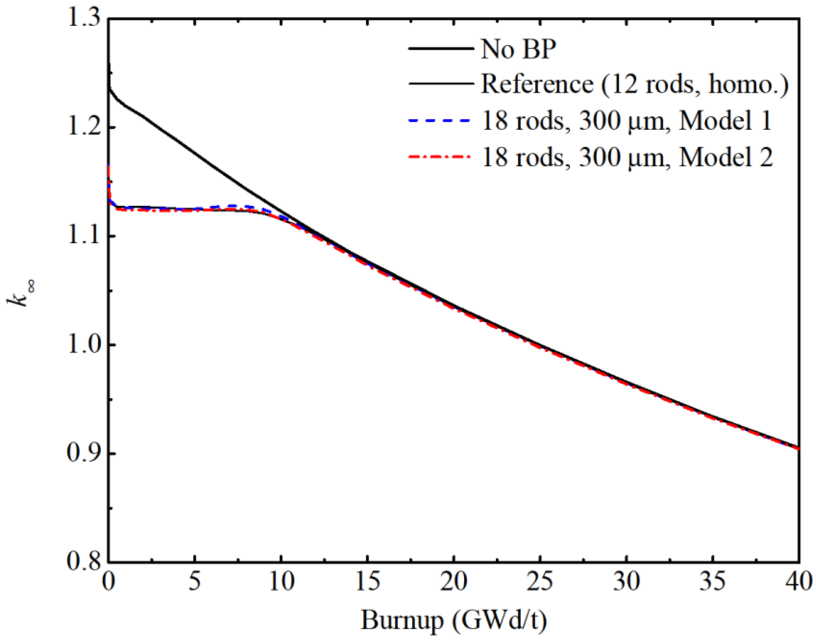

Fig. 5 The k_∞ curve of the VVER-1000 assembly with 18 UO_2-Gd_2O_3 rods.

Optimization of the BPP parameters such as the diameter and the packing fraction is performed. It is predicted that the total initial amount of Gd_2O_3 loaded in the newly designed fuel assembly would be the same as that in the reference one. Thus, the total amount of Gd_2O_3 in 12 rods of the reference design is distributed equally to 18 rods in form of BPPs. The packing fraction of BPPs in the fuel rods is determined as 3.33%. Calculations were then conducted to determine the optimal diameter of BPPs for obtaining the k_∞ curves during burnup similar to that of the reference design. Fig. 5 shows the effect of the BPP diameter on the k_∞ curve in the early burnup stage of the new fuel assembly designed with 18 BPP-dispersed fuel rods in Model 1 (see Fig. 4). The diameter of Gd_2O_3 particles was examined in the range of 200-360 μm, and the optimal diameter of 300 μm was selected as shown in Fig. 5. The same optimal diameter of the BPPs were obtained for Model 2. Fig. 6 depicts the k_∞ curves of the two optimal cases as functions of burnup. Comparing with the reference design the k_∞ curves of the new designs with 18 UO_2-Gd_2O_3 fuel rods are approximate.

The largest pin power densities appear at the peripheral fuel pin in both two models. The values are 1.105 and 1.113 for Model 1 and Model 2, respectively. Fig. 6 depicts the evolution of the PPF as a function of burnup of the new fuel assembly with 18 Gd_2O_3-dispersed fuel rods. The PPFs appears at the burnup of 0 GWd/t in both Model 1 and Model 2. The PPFs of the new assembly designed with 18 Gd_2O_3-dispersed rods is reduced by about 4.8% and 4.2% in Model 1 and Model 2, respectively. The results implies the possibility of using BPPs in the fuel rods for improving the neutronics performance of the VVER-1000 assembly.

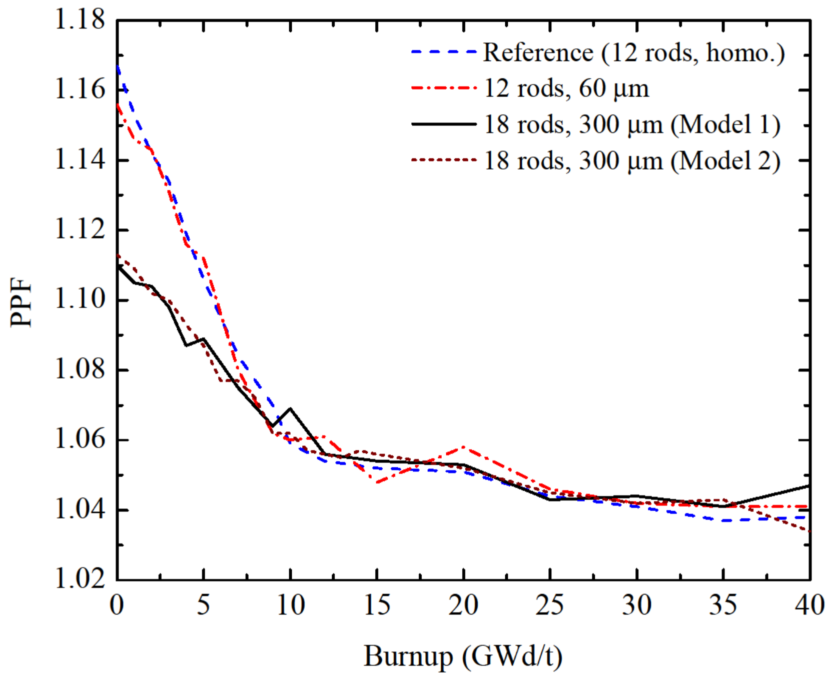

Fig. 6 PPF as a function of burnup of the VVER-1000 assembly with 18 UO_2-Gd_2O_3 rods.

3. CONCLUSION

Neutronics design of new VVER-1000 fuel assembly using micro-particles of Gd_2O_3 in the UO_2 fuel pellet for reactivity controlling has been carried out. The results show that with the same amount of BP (5% in volume) distributed in 12 rods in form of particles and the diameter of 60 μm, the reactivity curve and the power distribution of the new fuel assembly are approximate that of the reference one. To decrease the PPF, more uniform distribution of BPPs in the fuel assembly has been investigated. Two models of fuel assembly with 18 BPP-dispersed fuel rods were selected for optimizing the BPP parameters and evaluating the neutronics performance. The optimal diameter of 300 μm and the packing fraction of 3.33% were determined for both two models. The reactivity curves are obtained approximately that of the reference one while the PPF is decreased by about 4.8% and 4.2% in Model 1 and Model 2, respectively. Further application of the BPPs is being investigated for reducing soluble boron content in the coolant.

4. ACKNOWLEDGEMENTS

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5. REFERENCES

1. S. Fukushima, T. Ohmichi, A. Maeda, H. Watanabe, The effect of gadolinium content on the thermal conductivity of near-stoichiometric (U,Gd)O_2 solid solutions, *J. Nucl. Mat.* **105** (2) (1982) 201-210.
2. M. Amaya, M. Hirai, H. Sakurai, K. Ito, M. Sasaki, T. Nomata, K. Kamimura, R. Iwasaki, Thermal conductivities of irradiated UO_2 and (U,Gd)O_2 pellets, *J. Nucl. Mat.* **46** (7) (2002) 673-676.
3. K. Iwasaki, T. Matsui, K. Yanai, R. Yuda, Y. Arita, T. Nagasaki, N. Yokoyama, I. Tokura, K. Une, K. Harada, Effect of Gd_2O_3 dispersion on the thermal conductivity of UO_2, *J. Nucl. Sci. Technol.* **300** (1) (2009) 57-64.
4. H.N. Tran, H.T.P. Hoang, P.H. Liem, Feasibility of using Gd2O3 particles in VVER-1000 fuel assembly for controlling excess reactivity, *Energy Procedia* **131** (2017) 29-36.
5. NEA/NSC/DOC 10, A vver-1000 LEU and MOX assembly computational benchmark, Tech. rep., Nuclear Energy Agency, Organization for Economic Co-operation and Development (2002).
6. Y. Nagaya, K. Okumura, T. Mori, M. Nakagawa, MVP/GMVP II: General purpose Monte Carlo codes for neutron and photon transport calculations based on continuous energy and multigroup methods, JAERI-1348 (2005).
7. K. Shibata, T. Kawano, T. Nakagawa, O. Iwamoto, J.-I. Katakura, T. Fukahori, et al., Japanese evaluated nuclear data library version 3 revision-3: JENDL-3.3, *J. Nucl. Sci. Technol.* **39** (11) (2002) 1125-1136.

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Tóm tắt: Nghiên cứu ứng dụng Gd_2O_3 dạng hạt đã được thực hiện nhằm nâng cao các đặc trưng hạt nhân của bó nhiên liệu lò phản ứng VVER-1000. Các tính toán số được thực hiện nhằm tối ưu hóa các thông số của hạt hấp thụ sử dụng chương trình MVP và thư viện dữ liệu JENDL-3.3. Kết quả cho thấy bằng việc sử dụng các hạt Gd_2O_3 với đường kính 60 µm và tỉ lệ thể tích 5% đường cong độ phản ứng và phân bố công xuất trên các thanh nhiên liệu là xấp xỉ với thiết kế truyền thống. Để cực tiểu hóa hệ số đỉnh công suất (PPF), hai mô hình bó nhiên liệu với 18 thanh chứa hạt BPP được lựa chọn sao cho đường cong độ phản ứng xấp xỉ với thiết kế truyền thống trong khi hệ số đỉnh công suất PPF giảm từ 1.167 xuống 1.105 và 1.113.

Keywords: *VVER-1000 assembly, burnable poison, burnup reactivity, power peaking factor.*