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Neutronics feasibility of using Gd_2O_3 particles in VVER-1000 fuel assembly

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Abstract. Neutronics feasibility of using Gd_2O_3 particles for controlling excess reactivity of VVER-1000 fuel assembly has been investigated. The motivation is that the use of Gd_2O_3 particles would increase the thermal conductivity of the $UO_2+Gd_2O_3$ fuel pellet which is one of the desirable characteristics for designing future high burnup fuel. The calculation results show that the Gd_2O_3 particles with the diameter of 60 µm could control the reactivity similarly to that of homogeneous mixture with the same amount of Gd_2O_3. The power densities at the fuel pin with Gd_2O_3 particles increase by about 10-11%, leading to the decrease of the power peak and a slightly flatter power distribution. The power peak appears at the periphery pins at the beginning of burnup process which is decreased by 0.9 % when using Gd_2O_3 particles. Further work and improvement are being planned to optimize the high power peaking at the beginning of burnup.

Keywords: *Fuel assembly, Gd_2O_3 particle, power distribution, and VVER.*

I. INTRODUCTION

In LWRs, Gd_2O_3 is loaded in several fuel assemblies as burnable poison for controlling excess reactivity of the fresh fuel and the reactor core at the beginning of burnup stage. The purpose is to avoid an excessively high power peak at some fresh fuel assemblies. After a burnup level of about 10-15 GWd/t, main absorbing isotopes, Gd^{155} and Gd^{157}, which are about 30% in the natural gadolinium, are depleted completely and the reactivity decreases with burnup similarly to other assemblies without Gd_2O_3. In conventional design, an amount of Gd_2O_3 within a few percent is mixed homogeneously with UO_2 in several fuel pins of a fuel assembly. Since Gd_2O_3 has a smaller thermal conductivity than that of UO_2, its content leads to the decrease of the thermal conductivity of the fuel pellet [1]-[3]. In order to avoid the problem, the use of Gd_2O_3 particles in the UO_2 matrix could be a solution. It was reported that the thermal conductivity of Gd_2O_3-dispersed UO_2 is larger than that of $(U,Gd)O_2$ solid solutions with the same Gd_2O_3 content [3].

Iwasaki et al. [4] conducted experiments to investigate the effect of Gd_2O_3 dispersion on the thermal conductivity. The results showed that 10 wt% Gd_2O_3-dispersed UO_2 pellet with the diameter of Gd_2O_3 particles of about 25-53 µm has the thermal conductivity of about 5.8-2.7 W/mK in the temperature range from 300 to 1273 K. This is larger than that of homogeneous mixed solid solutions

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(3.8 to 2.6 W/mK) with the same Gd_2O_3 content [4]. This means that the use of Gd_2O_3 particles could improve the thermal conductivity of UO_2-Gd_2O_3 pellets effectively. For the purpose of the reduction of fuel costs, power upgrade and advanced fuel design with high burnup is desirable. Since power upgrade and high burnup fuel lead to the increase of the power density, the increase of the thermal conductivity of the fuel pellets would be one of the desirable characteristics of fuel. Regarding the fabrication possibility of the Gd_2O_3-dispersed UO_2 fuel pellet, as mentioned in Ref. [4] it was processed similarly to the traditional fuel pellet with Gd_2O_3 powder. Gd_2O_3 particles are weighted and mixed with UO_2 powder in a mortar. The mixture was then pressed into a form of fuel pellet and sintered under a high pressure and high temperature condition.

In the present work, we investigated, in neutronics point of view, the feasibility of using Gd_2O_3 particles for reactivity controlling and the effect on the neutronics performance of the VVER-1000 fuel assembly. Spherical Gd_2O_3 particles were distributed randomly in the UO_2 matrix of fuel pellet. The size of the Gd_2O_3 particles was determined for controlling the reactivity of the fuel assembly during burnup so that the target is to obtain the k_∞ curve similarly to that of the conventional fuel assembly. Comparison of the pin-wise power distribution between the new design and the conventional assembly has also been presented.

II. CALCULATION MODEL

Numerical calculations have been performed based on the low enriched UO_2 fuel assembly of VVER-1000 reactor core using the Monte Carlo neutron transport MVP code and the JENDLE-3.3 library [6],[7]. The configuration and the detailed design parameters of the fuel assembly are displayed in Fig.1Fig. 1 and Table . The assembly consists of 300 UO_2 fuel pins with the ^{235}U enrichment of 3.7 wt% and 12 $UO_2+Gd_2O_3$ fuel pins as shown in Fig. 1. In the numerical calculation model, spherical Gd_2O_3 particles are assumed to be distributed randomly in the UO_2 matrix of the fuel pellet. The statistical geometry (STG) model of the MVP code allows simulating the random distribution of the Gd_2O_3 particles. In the calculations, the history number of 25×10^6 is chosen to achieve the relative statistic error of the k_∞ within 0.01%. Calculations have been performed for two models of the fuel assembly: one with the homogeneous distribution of Gd_2O_3 powder in the UO_2 fuel pins, and the other with the distribution of Gd_2O_3 particles.

Table I. Design parameters of the VVER-1000 fuel assembly [5]

Parameters	Values
Number of central tube cell (-)	1
Number of guide tube cell (-)	18
Number of fuel cell with Gd (-)	12
Number of fuel cell (-)	300
Fuel cell inner radius (cm)	0.3860
Fuel cell outter radius (cm)	0.4582
Central tube cell inner radius (cm)	0.5450
Central tube cell outter radius (cm)	0.6323
Cell pin pitch (cm)	1.2750
Fuel assembly pitch (cm)	23.6
Non-fuel zones temperature (K)	575.0
Fuel zones temperature (K)	1027.0
Fuel (wt% ^{235}U)	UO_2 (3.6)
Gd_2O_3 density (g/cm^3)	7.4
Boron concentration (g/cm^3)	0.7235

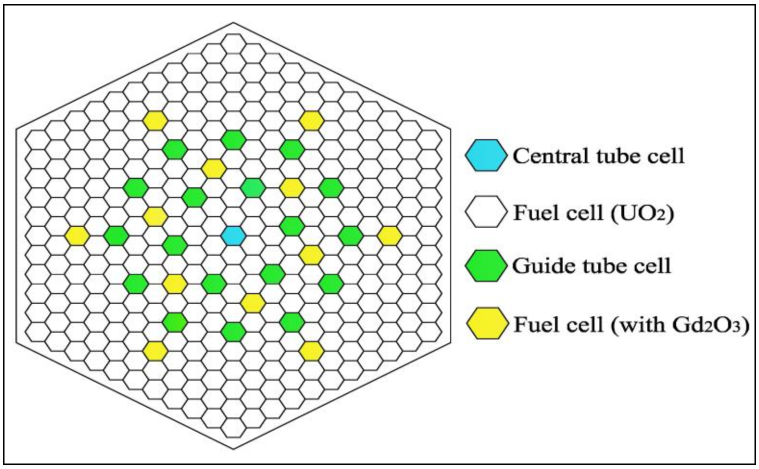

Fig. 1. Configuration of fuel assembly

III. RESULTS AND DISCUSSIONS

In the present work, we investigate the use of Gd_2O_3 particles instead of homogeneous distribution for the purpose of reactivity controlling and improving the thermal conductivity of the fuel pins. The size of the Gd_2O_3 particles is determined so that the k_∞ of the fuel assembly is controlled similarly to that of the conventional fuel. In the conventional design, the k_∞ of the fuel assembly is controlled from the beginning of burnup upto about 10 GWd/t. After this burnup level, most of the absorbing isotopes are depleted and the k_∞ decreases similar to that of the fuel assembly without Gd_2O_3. Thus, in the first stage of this design, we set the target to obtain a similar k_∞ curve of the new fuel assembly compared to that of the conventional design. Previous works used Gd_2O_3 particles for controlling the reactivity of a fuel pebble of a pebble bed reactor upto 60-100 GWd/t. Therefore, the radius of the particles of 820 or 950 µm was selected [8],[9]. However, in the current design of the fuel assembly we aim at controlling the reactivity upto 10 GWd/t, so that the radius of the particles could be predicted much smaller than 820 or 950 µm, and therefore, the self-shielding effect of the particles is also smaller.

In the calculation procedure, we assume that the same Gd_2O_3 amount is loaded into the fuel pins, i.e. 5% of volume, as in the conventional assembly. Then, a parametric survey was conducted to optimize the diameter of the Gd_2O_3 particles for reactivity control. shows the effect of the diameter of the Gd_2O_3 particles on the reactivity curves of the f**u**el assembly in the burnup range from 0 to 10 GWd/t with the diameter varying from 40 to 100 µm. Since we aims at finding a reactivity curve close to the conventional one in this burnup range, the diameter of 60 µm was selected for further calculations. Fig. 3 displays the k_∞ curve of the new fuel assembly with the Gd_2O_3 spherical particles having the diameter of 60 µm and the packing fraction of 5% (the volume ratio of the Gd_2O_3 particles and the matrix base in the STG model). This k_∞ curve is similar to that of the conventional design with homogeneous mixed Gd_2O_3. Other neutronics characteristics were also computed and compared to that of the conventional design. Fig. 4 displays the change of the ^{155}Gd and ^{157}Gd densities as a function of bunrup in the two designs. It is noted that the change of the Gd densities is slightly different between two cases because the particles with the diameter of 60 µm have small self-shielding effect and its function is slightly similar to the homogeneous distribution.

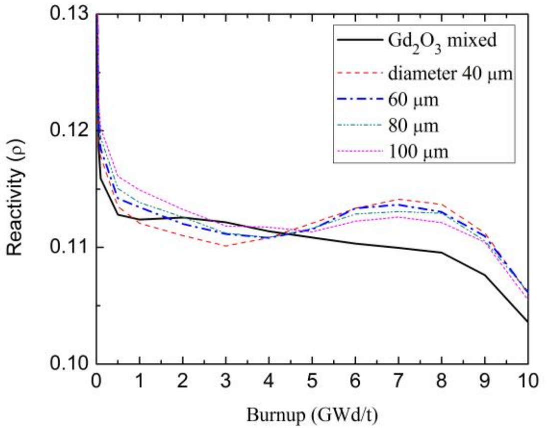

Fig. 2. Effect of the diameter of Gd_2O_3 particles on the reactivity of the fuel assembly at the beginning of burnup

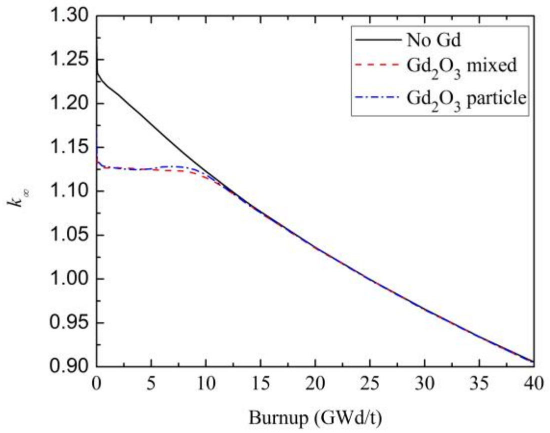

Fig. 3. The k_∞ as a function of burnup of the VVER-1000 fuel assembly. The diameter of 60 μm was selected

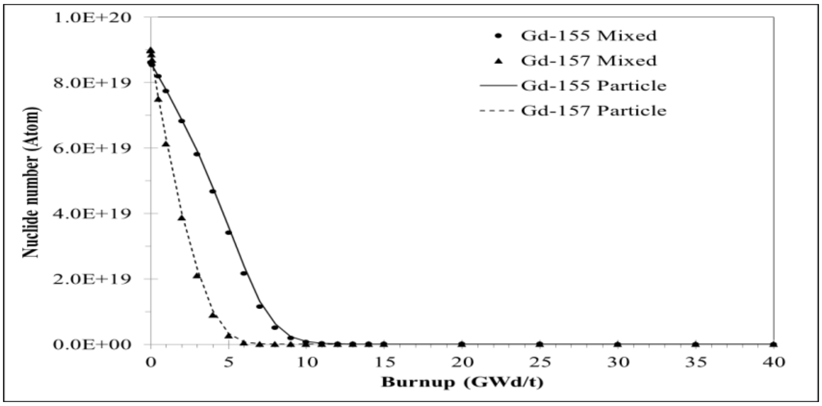

Fig. 4. Densities of ^{155}Gd and ^{157}Gd with burnup

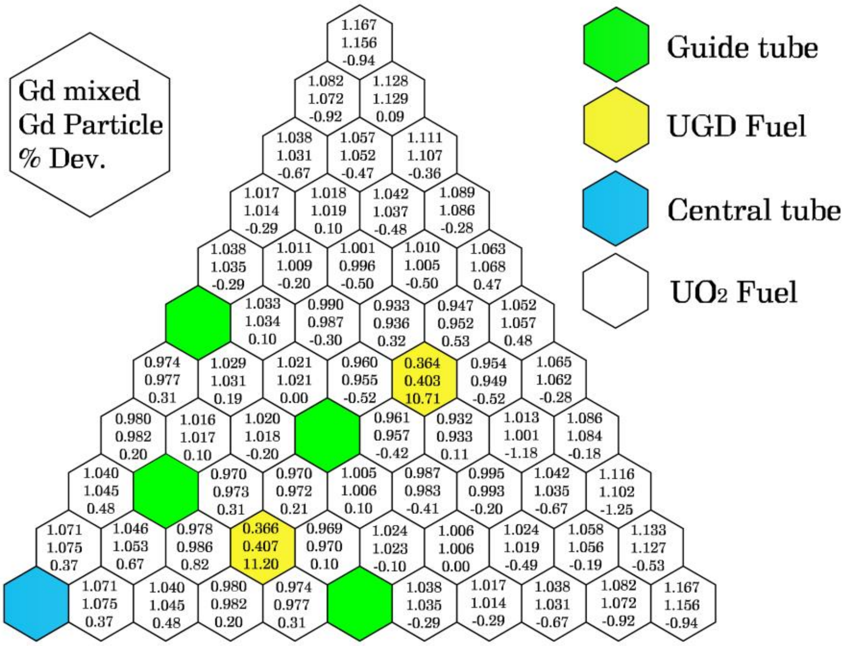

Fig. 5. Comparison of pin-wise power distribution at 0 GWd/t

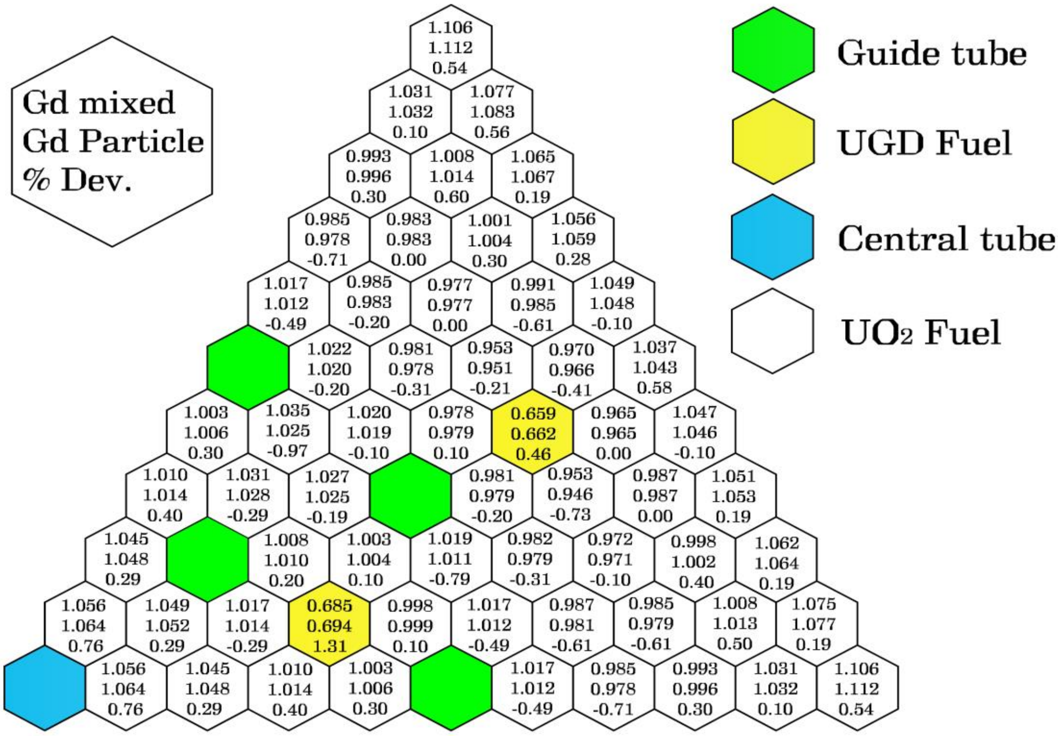

Fig. 6. Comparison of pin-wise power distribution at 5 GWd/t

Fig. 5 displays the pin-wise power distribution at the beginning of burnup (0 GWd/t) in the new designed fuel assembly with Gd_2O_3 particles in comparison with that of the conventional assembly. The figure shows the power in the 1/6th of the fuel assembly due to the symmetrical geometry. One can see that at the two UO_2+Gd_2O_3 fuel pins, the relative power densities at 0 GWd/t increase about 11% when using Gd_2O_3 particles compared to the that of fuel pin with Gd_2O_3 mixed homogeneously with UO_2. At other fuel pins, the relative power densities decrease within 0.6% in the outer region and increase within 0.8% in the central region. As a result, the power peak appearing at the periphery fuel pin decreases by 0.9% (from 1.167 to 1.156). This means that by using the Gd_2O_3 particles, the pin-wise power distribution of the fuel assembly becomes slightly flatter.

Fig. 6 and Fig. 7 show the same pin-wise power distribution as Fig. 5 but at the burnup levels of 5 and 10 GWd/t since in this burnup stage the Gd_2O_3 still has effect on the characteristics of the fuel assembly. At these burnup steps, the relative power at the Gd_2O_3 -dispersed fuel pins increases upto 1.8% compared to that of the conventional assembly. At these burnup, part of the Gd_2O_3 particles has been burnt, and the function of the Gd_2O_3 particles approaches to the homogeneous distribution. This means that the difference of relative power in the Gd_2O_3-dispersed fuel pin is smaller compared to that at the beginning of burnup stage (0 GWd/t).

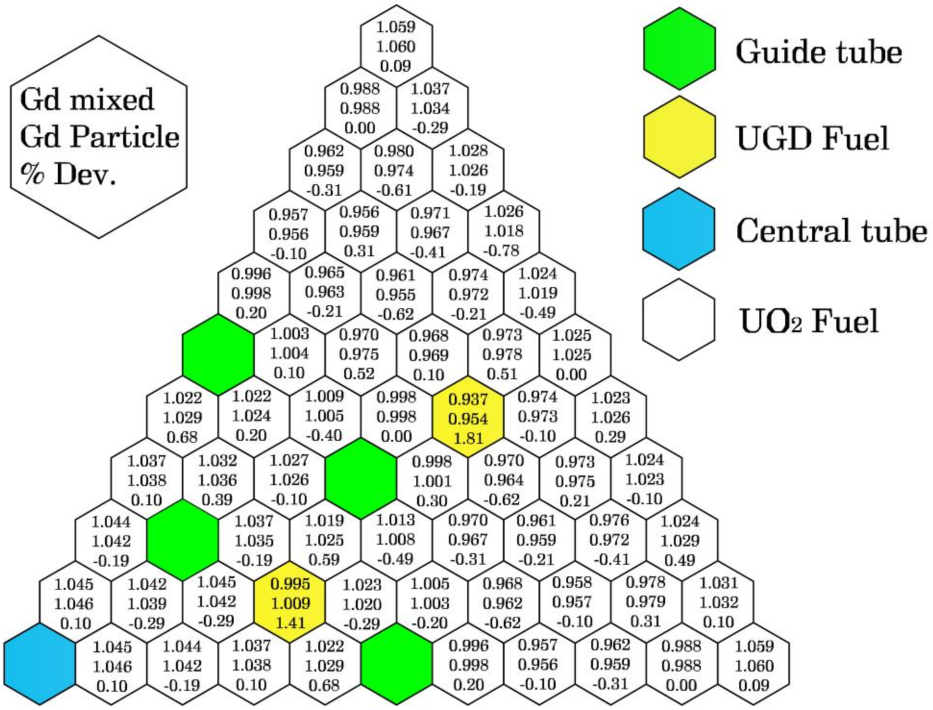

Fig. 7. Comparison of pin-wise power distribution at 10 GWd/t

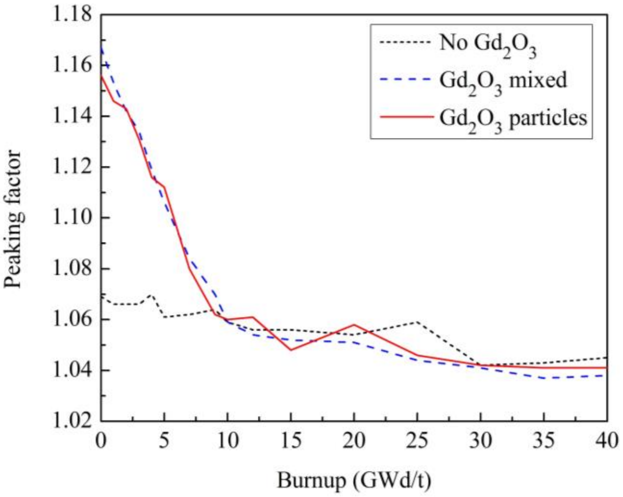

Fig. 8. Pin-wise power peaking factor during burnup

Fig. 8 depicts the pin-wise power peaking factor as a function of burnup of the new fuel assembly in comparison with that of the conventional design. The power peaking factor is greater in the burnup stage of 0-10 GWd/t when the Gd_2O_3 amount has effect on the reactivity. The power peaking factor decreases with burnup and becomes slightly stable around the value of 1.040-1.060 after 10 GWd/t. By using the Gd_2O_3 particles the power peaking factor decreases slightly by about 0.9% at the beginning of burnup. However, the main merit achieved for the new fuel assembly with Gd_2O_3 particles is the increase of the thermal conductivity of the fuel pellet [4]. The results obtained in this preliminary investigation show that in the neutronics point of view it is feasible to use Gd_2O_3 particles instead of powder in the UO_2 fuel pellet for excess reactivity controlling, while the main neutronics characteristics could be obtained similarly to that of the conventional design. From the evolution of the power peaking factor with burnup as shown in Fig. , it suggests that the further investigation should be conducted to flatten the power peaking in the early burnup stage of the fuel assembly.

IV. CONCLUSIONS

Investigation of the neutronics feasibility of using Gd_2O_3 particles in the UO_2 fuel pellet of the VVER-1000 fuel assembly has been conducted. The motivation is that by using Gd_2O_3 particles instead of powder the thermal conductivity of the UO_2+ Gd_2O_3 fuel pellet would increase [4]. The results show that with the same content of 5% in volume, Gd_2O_3 particles with the diameter of 60 µm control reactivity similarly to the homogeneous mixture. The power density at the fuel pin with Gd_2O_3 particles increases by about 11% at the beginning of burnup which leads to the slight decrease of power peak and slightly flatter power distribution. The power peak appearing at the periphery pins at the beginning of burnup decreases by 0.9% when using Gd_2O_3 particles. The results demonstrate that by loading the same amount of Gd_2O_3 but in form of particles with the diameter of 60 µm instead of the powder in the UO_2 fuel pellet, the neutronics properties of the new fuel assembly could be obtained similarly to that of the conventional design.

In the future work, further investigation are being conducted to optimize the high power peaking at the beginning of burnup using Gd_2O_3 particles. Thermal hydraulics analysis of the new fuel assembly will also be investigated in order to estimate the advantage of the new design.

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