Study of keff values of different distributions and types of burnable poisons in VVER-1000 reactor using SuperMC

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Abstract. This paper presents the impact of different types of burnable poisons and filling methods on burnup in the VVER-1000 reactor. In this study, SuperMC was used to visually model the fuel assembly of the VVER-1000 reactor, perform burnup calculations and compare the results. Five groups (Homogeneous Gd2O3, Heterogeneous Gd2O3 1 and 2, Homogeneous AmO2, Pure UO2) of different burnable poisons are modeled with fuel assembly as a unit, and the results will be analyzed by comparing the difference of keff.

1. Introduction

1.1. Burnable poisons
In a light water reactor (LWR), burnable poisons (BPs) are usually added in a number of fuel rods of several assemblies for controlling excess reactivity in the early burnup stage of the fresh fuel [1]. As a result, excess reactivity is reduced and power distribution in the core is flattened to avoid a high power peaking factor at fresh fuel assemblies.

1.2. K-effective
In the multiplication system of the reactor, the neutrons produced by the fission reaction cause the fission of other isotopes, this process is called the chain fission reaction. If the fission reaction continues without relying on external effects, this process is called the self-sustained fission chain reaction. The conditions of the self-sustained fission chain reaction in the reactor can be expressed simply by the effective multiplication factor (keff), that is, the ratio of the number of neutrons in the new generation to the number of neutrons in the previous generation. However, there will be neutron loss in the fission reaction, so it is actually more convenient to define keff from the balance relationship of neutrons, as follows:

\[
keff = \frac{\text{Neutron production rate in the system}}{\text{The total disappearance rate of neutrons in the system (absorption + leakage)}}
\]  

The following three cases discuss the value of keff.

keff < 1. At this time, the number of neutrons in the system will continue to decay over time, and the chain reaction cannot be maintained. This state is called the subcritical state.
keff > 1. At this time, the number of neutrons in the system will continue to increase over time, and this state is called the supercritical state.

keff = 1. At this time, the number of neutrons in the system will not change with time, and the chain reaction remains stable. This state is called a critical state.

1.3. SuperMC
Monte Carlo (MC) methods have been widely used in nuclear design and analysis of advanced nuclear energy systems. However, the current MC method still has great challenges, including the modeling of complex geometries, the simulation of deep penetration problems in radiation shielding, the slow convergence speed of complex calculations, and the lack of experimental verification of new physical features.

Super Monte Carlo Nuclear Simulation Software (SuperMC) is a set of universal, intelligent and accurate nuclear design and radiation safety evaluation software developed by the FDS team of the Institute of Nuclear Energy Safety Technology of the Chinese Academy of Sciences [2]. It supports neutronics-related calculations with radiation transport as the core, including burnup, radiation source terms, doses, biological hazards, material activation and transmutation, and other neutronics related calculations; and supports thermal hydraulics, structural mechanics, chemistry, biology and other physics Coupling simulation. The currently released version (2.3) can perform neutron, photon and coupled transport simulations, and can be widely used in nuclear reactor design, radiation physics calculations, medical physics simulation, nuclear detection, and high-energy physics simulation research.

SuperMC has developed a CAD-based automatic intelligent modeling function, which can significantly reduce manpower and improve the reliability of the calculation model [3]. CAD models represented by Boundary Representation method can be automatically converted to MC calculation geometry models which are represented in CSG based on primitive solids. In this process, SuperMC's automatic geometric fixation and high-order free-form surface simplification methods standardize the CAD model so that it can be converted into a high-quality simulation model.

1.4. The aim of study
In the light water reactor (LWR), the filling form of the burnable poisons will affect the fuel burnup of the reactor, and it is the keff value that can directly reflect the situation of fuel burnup. This study will use the SuperMC program to model the VVER-1000 reactor fuel assembly, perform burnup calculations and compare the results.

2. Model group description
In this study, the SuperMC program was used to model the fuel assembly of the VVER-1000 reactor. The fuel assembly parameters are shown in the below table, and the cross-section of the fuel assembly modeled using SuperMC is also shown below.

| Parameters                  | Unit | Value |
|-----------------------------|------|-------|
| Number of central tube      |      | 1     |
| Number of guide tube        |      | 18    |
| Number of fuel cell with Gd |      | 12    |
| Number of UO2 fuel cell    |      | 300   |
| Fuel center hole radius     | cm   | 0.075 |
| Fuel pellet radius          | cm   | 0.379 |
| Inner diameter of fuel cell | cm   | 0.387 |
Outer diameter of fuel cell cm 0.457
Central tube cell inner radius cm 0.5450
Central tube cell outer radius cm 0.6323
Pin pitch cm 1.2750
Fuel assembly pitch cm 23.6
Fuel temperature K 1027
Non-fuel temperature K 575
235U enrichment wt% 3.7/3.6
Gd2O3 density g/cm³ 7.4
AmO2 density g/cm³ 11.68

Figure 1. Cross-sectional view of fuel assembly.

As shown in the figure, in the model in the figure, cell 1 is special fuel cell (mixed with burnable poisons), cell 2 is pure fuel cell (only UO2), cell 3 is guide tube, and cell 4 is central tube.

In this study, five different fuel burnup situations were analyzed and compared. The size and value of the fuel assembly and all fuel rod cladding are exactly the same, the difference is in the composition and distribution of the burnable poison. In a fuel assembly, there are 18 fuel rods containing burnable poisons, and the remaining 300 fuel rods are pure UO2 and 12 guide tubes. The UO2 enrichment in all fuel rods is 3.7%, only the AmO2 homogeneous model UO2 enrichment is 4.95%.

The burnable poisons used in this simulation are Gd2O3 and AmO2, they have different forms (homogeneous or heterogeneous).

The five groups of models are different in the special fuel cell (mixed with burnable poisons). The following is the composition data of the burnable poisons of the special fuel cell in each model:
(1) homogeneous model 1 (UO2 95% + homogeneous Gd2O3 5%);
(2) heterogeneous model 1 (UO2 95% + heterogeneous Gd2O3 5%);
(3) heterogeneous model 2 (UO2 95% + heterogeneous Gd2O3 5%);
(4) homogeneous model 2 (UO2 95% Enrichment + 5% AmO2);
(5) pure UO2 (no burnable poison).

3. Research method
In this study, SuperMC program was used for modeling and burn up calculation to obtain the k\textsubscript{eff} results of VVER-1000 reactor in different situations.

The fuel assembly model has been shown above, and the models in the five groups of special fuel cells (mixed combustible poisons) will be described and explained in detail, and the distribution and detailed values of UO2 and combustible poisons in the fuel cell will be displayed. The same parts, such as central tube, guide tube and UO2 fuel cell will not be shown in this article.

3.1. Homogeneous Gd2O3 model 1 (UO2 95% + homogeneous Gd2O3 5%)

![Figure 2. Cross section of the fuel rod, the yellow part is the homogenous mixture of Gd2O3 powder and 3.7% UO2](image)

3.2. Heterogeneous Gd2O3 model 1 (UO2 95% + heterogeneous Gd2O3 5%)

![Figure 3. Gd2O3 part](image)  ![Figure 4. UO2 part(3.7%)](image)

The first doping method of Gd2O3 is that 108 Gd2O3 cylinders with a length of 300 cm and a diameter of 0.016 cm are embedded in UO2 fuel, and the total volume is 6.5144 cm\(^3\).

3.3. Heterogeneous Gd2O3 model 2 (UO2 95% + heterogeneous Gd2O3 5%)
The second doping method of Gd2O3 is that Gd2O3 is wrapped on the outer side of UO2 fuel pellet in the form of a layer of cylindrical wall. The length of the cylinder is 300 cm, the wall thickness of the cylinder is 0.0093 cm, and the total volume is 6.5263 cm³.

3.4. Homogeneous AmO2 model 2 (UO2 95% Enrichment + 5% AmO2) & Homogeneous AmO2 model 2 (UO2 95% Enrichment + 5% AmO2)

4. Results
Burnup calculation has been performed with a power density of 108 W/gHM up to a burnup of 40 MWd/kgHM with 40 burnup steps (1 MWd/kgHM in 0-40).

The keff value of the burnup result is shown in Figure 9.
5. Conclusion.
The pure UO2 group has no burnable poisons, so the keff value is the highest at the beginning. But if the UO2 enrichment of the fuel unit of all groups is the same (3.7%), their keff values will be the same in the later stage, regardless of whether there are burnable poisons or not.

Comparing the two combustible poisons, Gd2O3 and AmO2, their keff curve has a flat period in the beginning due to the effect of neutron absorption, and then the keff begins to decrease with the consumption of Gd and Am. It can be seen that the keff curve of Gd2O3 has a longer flattening time, indicating that Gd2O3 is more effective as a burnable poison. It can be used to absorb large initial delayed reactivity, deepen the burn up and flatten the distribution of neutron fluence rate.

Comparing three sets of models of Hom1, Het1 and Het2, it can be found that when combustible poisons are uniformly applied to the outer sides of the fuel pellet in the form of a cylindrical wall, the trend of the burn up keff curve of Hom1 and Het2 is very close. It shows that these two ways of filling burnable poisons are equivalent and can replace each other. This will give guidance for the actual filling of burnable poisons in fuel rods, for example, how to choose the best way in consideration of economic benefits and time costs.

References
[1] HN Tran, VK Hoang and PH Liem 2019 Neutronics design of VVER-1000 fuel assembly with burnable poison particles Nuclear Engineering and Technology vol 51(7) pp 1729-1737
[2] Wu YC, Song J, Zheng HQ, et al 2015 CAD-based Monte Carlo Program for Integrated Simulation of Nuclear System SuperMC Annals of Nuclear Energy vol 82 pp 161-168
[3] Wang GZ, Xiong J, Long PC, et al 2011 Progress and Applications of MCAM: Monte Carlo Automatic Modeling Program for Particle Transport Simulation Progress in Nuclear Science and Technology vol 2 p 821