Simulation of the Efficiency of Black and Gray Absorbers and their Effect on Criticality in VVER-1000 Fuel Assemblies

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***Keywords :** control rods, gray control rods, criticality, VVER-1000 fuel assembly

1. Introduction

The growing share of renewable energy sources (RES) in the power grid-particularly photovoltaic and wind power plants is placing increasingly demanding requirements on the flexibility of the other sources connected to the power grid. These demands will be placed not only on current operating nuclear units but also on future units, such as small modular reactors (SMRs), for which flexible operation should already be incorporated into the conceptual design.

The most commonly used way of power control in light water reactors involves the use of black absorbers, such as those made of boron carbide (B_4C). This method of power regulation is suitable for operation in the base load range, where significant changes of power or the provision of operational flexibility are not considered.

An alternative way of power control is the use of gray absorbers, also known as gray control rods (GCR) [1]. These control rods (CR) have a lower ability to absorb thermal neutrons compared to black control rods [2]. The lower worth of gray control rods allows them to be inserted deeper into the core. The neutron flux density is thus less distorted, and as a result, both the axial and radial power distributions in the core are less distorted, and heat generation in the reactor core is more uniform. A more uniform axial power distribution reduces the axial offset in the core. A gray control rod typically consists of a combination of black rods (e.g. B_4C) and gray rods (e.g. stainless steel) [3]. The specific types of gray control rods simulated are described in the following section.

2. Case study and Results

2.1 LR-0 reactor

The simulated configuration is a model of LR-0 research reactor located at Research Centre Řež. The reactor is a light-water, zero-power experimental reactor used for measuring neutron-physical characteristics, model reactor cores and verify nuclear data and computer codes [4]. The model of the LR-0 reactor was simulated because experiments based on the results of these simulations are planned to be conducted on this facility in the future.

The LR-0 is versatile, it is possible to configure various reactor core with VVER-440 or VVER-1000 hexagonal fuel assemblies (FA). The fuel assemblies can be assembled from fuel rods with different enrichment levels. It is also possible to use fuel rods with burnable absorbers. Criticality is reached by filling the reactor core with water to the critical height, above which the fuel remains dry [4]. A model of the LR-0 reactor is shown in Figure 1.

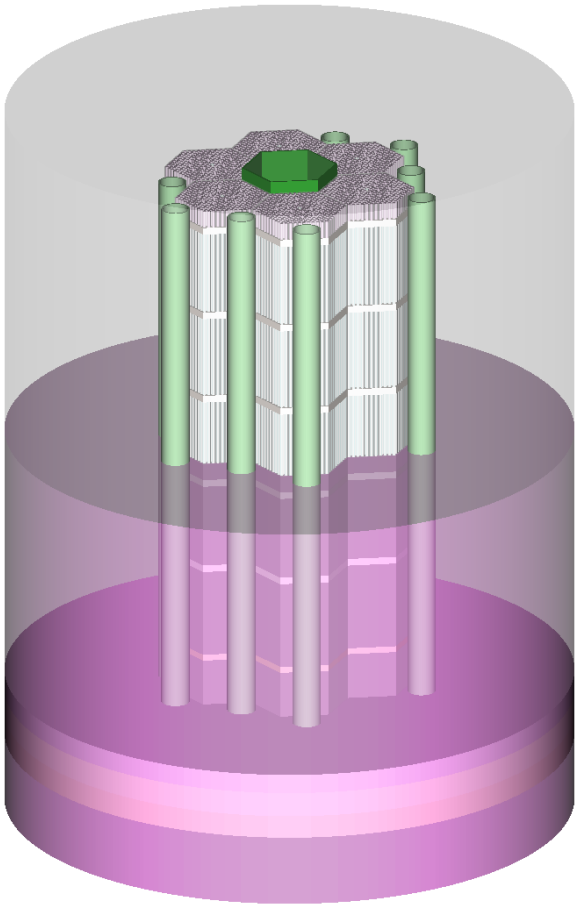


Fig. 1. Model of the LR-0 simulated reactor

2.2 Reactor model design

All simulations were performed using the SCALE computational code, version 6.3 [5]. The specific sequence used was CSAS6, which is a criticality safety analysis using KENO VI. The KENO VI is the 3D stochastic (Monte Carlo) transport code. It is one of the tools used for criticality safety analysis. KENO uses the SCALE Standard Composition Library and the SCALE Generalized Geometry Package, which allows for versatile modeling of complex geometries (such as the LR-0 reactor). The code determines the effective multiplication factor of a system by simulating a large number of neutron histories and generations to achieve statistically reliable results of k_{eff} [5].

The fuel assembly was created using the array method, in which the individual cells (the fuel pins, the guide tubes, the central tube) are first defined. The cells are then inserted into the fuel lattice. The library used was ENDF/B-VII.1 Continuous-energy neutron and gamma library. In the simulations, the parameters were set to 5000 neutron generations with 50 000 histories per generation, for a total of 250 million simulated neutron histories. The first 100 generations (5 million histories) were skipped to allow the spatial distribution of the fission source to converge prior to the actual calculation. The resulting value of the k_{eff} and its statistical uncertainty were thus evaluated from 4 900 active generations, which ensures sufficient statistical accuracy of the results.

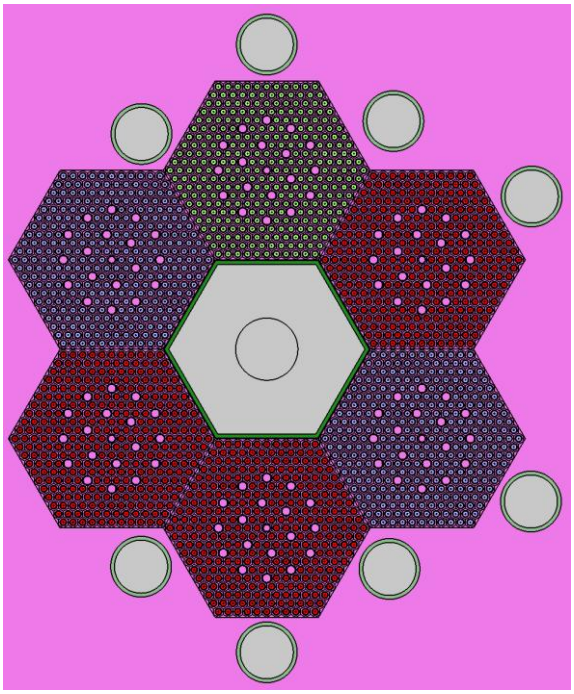


Fig. 2. Radial cross-section of the core

The reactor core consists of 6 unprofiled fuel assemblies with three different fuel enrichments. One FA enriched to 3.28% ^{235}U (green), two FA enriched to 3.29% ^{235}U (blue), and three FA enriched to 3.0% ^{235}U (red). The core further comprises eight aluminum measuring channels located around the FA, as well as one central hexagonal experimental channel, also made of aluminum [4]. A radial cross-section of the core without control rods is shown in Fig. 2, the parameters are listed in Tab. 1, where w/o % denotes weight percent, i.e., the mass fraction of the ^{235}U isotope relative to the total uranium mass in fuel.

Table 1. Parameters of simulations

Parameter	Value
Number of FA in core	6
Number of pins in FA	312
Number of void tubes in FA	18
Fuel enrichment	3.28 (w/o %) 1 FA
Fuel enrichment	3.29 (w/o %) 2 FA
Fuel enrichment	3.30 (w/o %) 3 FA
Critical-height	55.6 cm

2.3 Simulated Cases

The first simulated case did not use black or gray control rods. The simulation was set up for this study as a reference, in this case k_{eff} reached a value close to 1. The exact results are presented in the following section. The configuration is shown in Fig. 2. For this case and all subsequent simulations, the moderator level was fixed at the computationally determined critical height, so that negative reactivity was introduced into the core only by the control rods.

The second case was simulated using a black control rods (B_4C) that were fully inserted into a fuel assembly with an enrichment of 3.28% ^{235}U. The black absorber was used as a reference value for comparing the worth (efficiency) of gray control rods with that of a conventional black control rod. A detailed view is shown in Fig. 3.

The third case simulated a gray control rod consisting of 6 steel rods and 12 B_4C rods, designated as GCR1 in the Table 2, with its configuration shown in Fig. 4. The fourth case involved a control rod composed of 9 steel rods and 9 B_4C rods (GCR2), whose configuration is shown in Fig. 5. In the fifth case, a control rod with 12 steel rods and 6 B_4C rods (GCR3) was used, with its configuration presented in Fig. 6. The sixth case represented a control rod consisting of 6 steel rods and 12 B_4C rods (GCR4), shown in Fig. 7. The seventh case involved a control rod with 12 steel rods and 6 B_4C rods (GCR5), whose configuration is shown in Fig. 8; although it has the same composition as GCR3, the rod arrangement differs. The eighth case simulated the use of two GCR5-type control rods inserted into two fuel assemblies enriched to 3.29% ^{235}U. In the ninth case, three GCR5-type control rods were used in three fuel assemblies enriched to 3.3% ^{235}U.

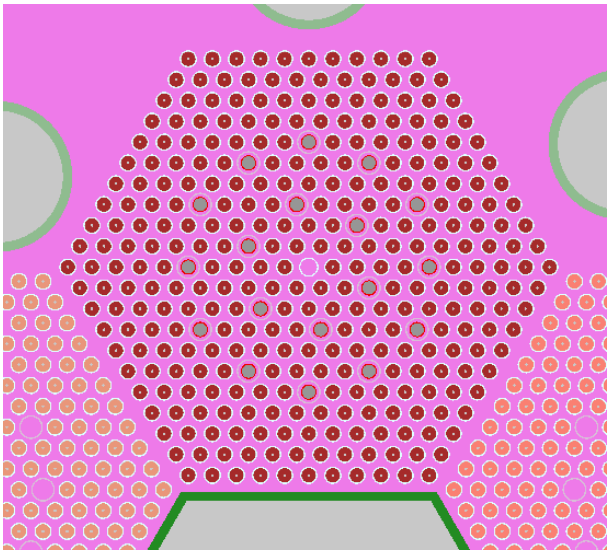


Fig. 3. Detail of the control rods B_4C

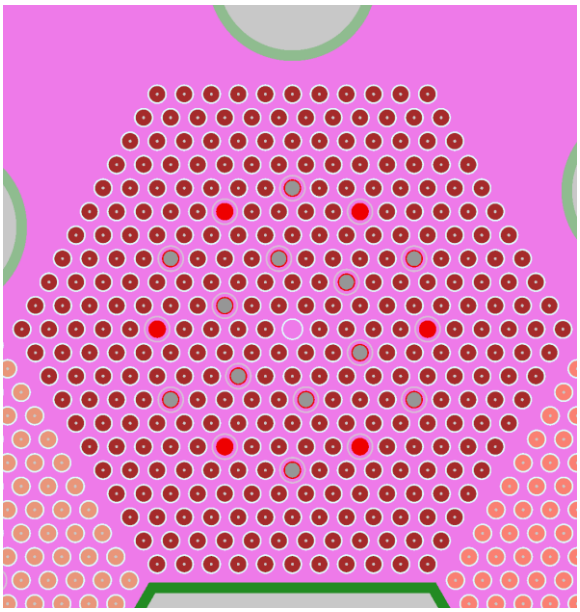


Fig. 4. Detail of the GCR1

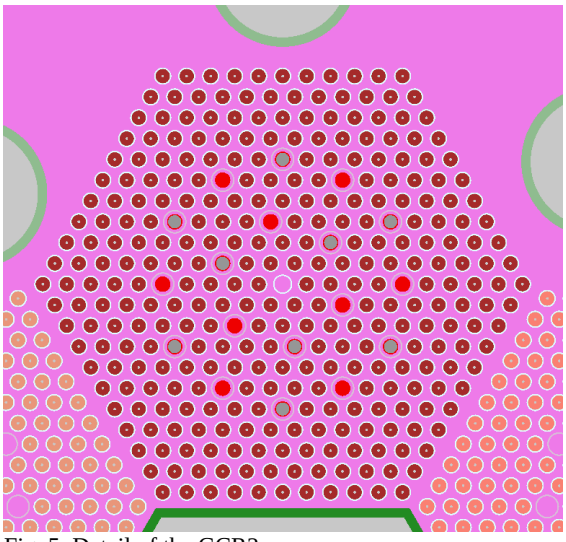


Fig. 5. Detail of the GCR2

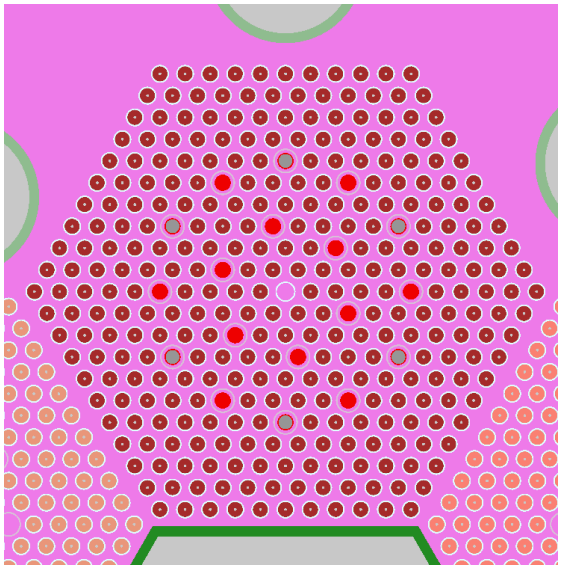


Fig. 6. Detail of the GCR3

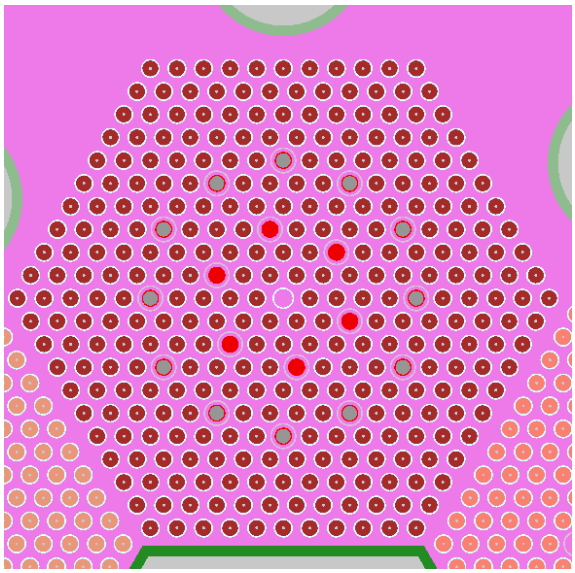


Fig. 7. Detail of the GCR4

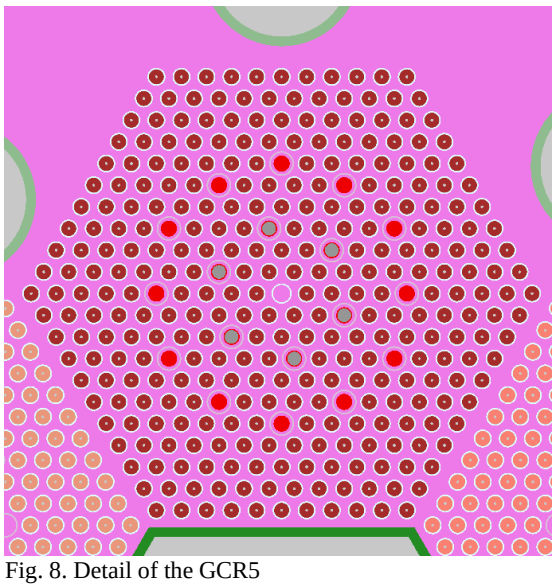


Fig. 8. Detail of the GCR5

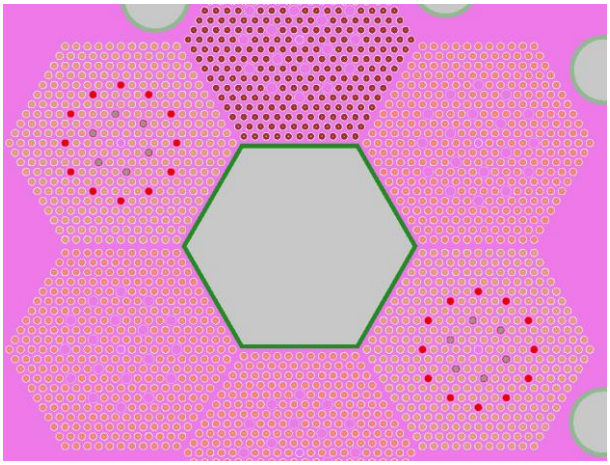


Fig. 9. Detail of the Case 8

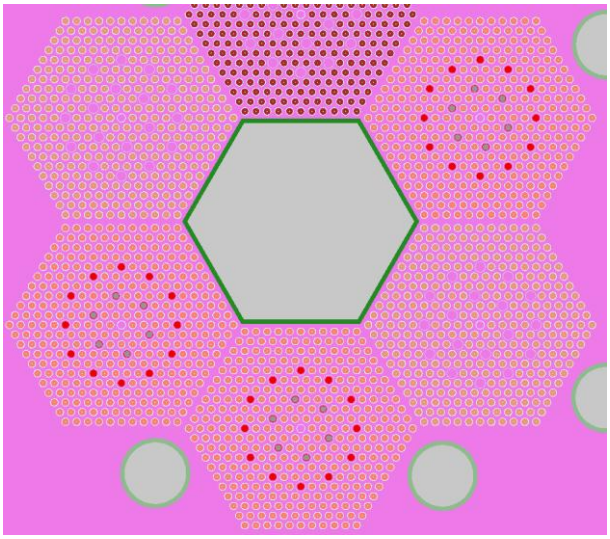


Fig. 10. Detail of the Case 9

2.4 Results

Table 2. Results of simulations

Case	k-eff
Case 1 (CR OUT)	0.999878 ± 0.000054
Case 2 (B_4C)	0.978510 ± 0.000053
Case 3 (GCR1)	0.982388 ± 0.000052
Case 4 (GCR2)	0.984664 ± 0.000051
Case 5 (GCR3)	0.987313 ± 0.000054
Case 6 (GCR4)	0.982067 ± 0.000052
Case 7 (GCR5)	0.987978 ± 0.000050
Case 8	0.973383 ± 0.000052
Case 9	0.959852 ± 0.000056

The simulation results presented in Table 2 compare the efficiency of the individual control rod types relative to the reference state without control rods (CR OUT k-eff = 0.999878 ± 0.000054) and relative to the reference black absorber B_4C (k-eff = 0.978510 ± 0.000053). The comparison shows that, among the single inserted rods, the black B_4C absorber exhibits the highest reactivity worth, while the gray control rods GCR1–GCR5 produce a smaller reduction in k-eff and thus lower efficiency, proportional to the fraction of steel rods in their composition. The lowest efficiency was observed for the GCR5 configuration (k-eff = 0.987978 ± 0.000050), whereas the highest efficiency among the gray rods was achieved by GCR3 (k-eff = 0.987313 ± 0.000054), confirming that the arrangement of rods within the assembly affects its resulting worth even for an identical ratio of absorbing material. Cases 8 and 9, in which two and three GCR5-type control rods were simultaneously inserted, respectively, demonstrated a pronounced cumulative effect: with two rods (Case 8), k-eff decreased to 0.973383 ± 0.000052, yielding an efficiency comparable to or exceeding that of the single B_4C rod, while with three rods (Case 9), k-eff decreased further to 0.959852 ± 0.000056, representing the largest reactivity reduction among all tested configurations. For clarity, Table 3 was created to present the differences in k-eff relative to reference case without control rods (CASE 1).

Table 3 Results of simulations

Case	Δk-eff (pcm)
Case 2 (B_4C)	-2137 ± 8
Case 3 (GCR1)	-1749 ± 8
Case 4 (GCR2)	-1521 ± 7
Case 5 (GCR3)	-1257 ± 8
Case 6 (GCR4)	-1781± 8
Case 7 (GCR5)	-1190 ± 7
Case 8	-2650 ± 8
Case 9	-4003 ± 8

The presented results are intentionally limited to the multiplication factor as the evaluated quantity, since k-eff (and the reactivity worth derived from it) is the same integral parameter targeted by the planned experiments. Critical experiments on the LR-0 reactor are traditionally designed to determine core criticality and the associated reactivity worth of inserted absorbers — typically via the critical moderator level or critical rod position — rather than to resolve the local power distribution within the assembly [4]. As the follow-up experimental verification of the black and gray absorber configurations studied here is planned along the same lines, the computational analysis was correspondingly focused on the consistent determination of multiplication factor across all evaluated configurations, so that the present results can serve as a direct predictive basis for interpreting the future experimental data. The assessment of the axial/radial power distribution and peaking factors, which would further substantiate the effect of gray versus black absorbers on the core power shape, is left to a follow-up study.

3. Conclusions

This study evaluated the effectiveness of gray control rods (GCR) as an alternative to conventional black B_4C absorbers for flexible power control in a VVER-1000 fuel assembly configuration modeled in the LR-0 research reactor, using the SCALE/KENO-VI Monte Carlo code. The results confirm that gray control rods, composed of a combination of steel and B_4C rods, consistently produce a smaller reduction in k-eff than a fully black B_4C rod, confirming their lower reactivity worth and, consequently, their suitability for deeper insertion during flexible operation without excessive local flux distortion. Among the five tested GCR configurations, the reactivity worth was found to depend not only on the steel-to-B_4C rod ratio but also on the internal arrangement of the rods within the cluster, as demonstrated by the differing results obtained for GCR3 and GCR5 despite their identical composition. The combined insertion of multiple GCR5 rods (Cases 8 and 9) showed a pronounced cumulative reduction in k-eff, indicating that gray control rod worth can be scaled by increasing the number of inserted assemblies to approach or exceed the worth of a single black absorber while retaining a more distributed axial and radial power profile.

It should be noted that the goal of this study was not to determine a safe number of rods or a reactivity worth limit with respect to reactor shutdown margin, but rather to investigate the effect of rod arrangement within the control rod cluster and the number of gray control rods inserted in the core on their resulting worth and efficiency. This study is intended as a preparatory step for a planned follow-up experiment on the LR-0 reactor at the Research Centre Řež in the Czech Republic, where the simulated configurations will be experimentally verified.

ACKNOWLEDGEMENT

This work is supported by the Technology Agency of the Czech Republic (TAČR) under project No. TA182604001.

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