

Computational analysis of a neutron trap in the center of the WWR-K reactor core for irradiation tests of large-sized objects

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DOI: 10.32523/ejpfm.2022060104

Received: 16.01.2022 - after revision

Nowadays, the WWR-K research reactor is operated with low-enriched uranium fuel and a beryllium neutron reflector. Irradiation positions located in the core make it possible to irradiate objects no larger than 50 mm in size. In the reactor tank, behind the beryllium reflector, there are irradiation positions with a diameter of 200 mm, but in them, in comparison with irradiation positions in the core, the neutron intensity is lower. This motivated us to carry out computational studies on the generation of a large diameter neutron trap in the center of the WWR-K reactor core. The paper presents the results of neutron-physical calculations on the generation of a neutron trap in the center of the WWR-K reactor core. The generation of a large diameter neutron trap in the core of the WWR-K reactor will make it possible to carry out radiation tests of large objects. For this, it is necessary to change the layout of the core. The influence of the transformation of the core on the experimental characteristics of the WWR-K reactor is shown.

Keywords: WWR-K; irradiation test; neutron trap

Introduction

The efficient use of a research nuclear reactor is one of the important tasks, the solution of which will optimize and reduce the operating costs of the facility.

In the modern world, research reactors have a wide range of applications. In particular, they are used for testing components and materials of fission and fusion reactors, production of radioisotopes, coloring of gemstones and neutron transmutation doping of silicon [1-14]. The listed areas of application require high neutron fluxes and sometimes large volumes of irradiation positions. If an increase in the neutron flux requires an increase in the power of a nuclear reactor, then for irradiation of large objects it is necessary to optimize the configuration of the core and install a neutron trap (irradiation position with a large diameter) [15-23].

The WWR-K reactor has numerous irradiation positions both in the core and in the reactor tank [24, 25]. In the reactor tank, the diameter of the irradiation positions varies from 60 to 200 mm, but these positions are low-flux. In the core, the irradiation of materials and objects is limited to a diameter of 50 mm, and they are in the greatest demand from customers of irradiation works, since these positions have the highest neutron flux. The support lattice of the reactor makes it possible to install a neutron trap in the center of the core instead of seven elements [26]. For example, a neutron trap was used during the life tests of three low-enriched experimental fuel assemblies. The power of the fuel assembly in the neutron trap was two times higher than in the most energetically stressed fuel assembly located in the core [27, 28]. In addition, such a neutron trap will make it possible to carry out irradiation tests of large objects. However, the number of irradiation positions in the center of the core will decrease and, possibly, the neutron trap will affect other irradiation positions, as a restructuring of the core configuration will occur. In this work, using the method of mathematical simulation, the possibility of creating a neutron trap with a diameter of 140 mm in the center of the WWR-K reactor core is considered and its effect on other neutronic characteristics is analyzed.

Materials and Methods

Mathematical simulation of the core of the WWR-K reactor with a neutron trap was carried out using the MCNP6 transport code and the ENDF/B-VIII library of nuclear data [29, 30]. In MCNP, the simulation of neutron transport in material environment is carried out using the Monte Carlo method. Specific applications include, but are not limited to, radiation protection and dosimetry, radiography, medical physics, nuclear safety, detector design and analysis, accelerator target design, fission and fusion reactor design, decontamination and decommissioning [29].

WWR-K is a research heterogeneous tank thermal reactor. The reactor operates with a beryllium reflector, light water moderator and coolant. The operating thermal power is 6 MW. The reactor was commissioned in 1967. The uranium fission chain reaction is controlled by six reactivity compensation rods and one automatic control rod. There are also three emergency protection rods. All rods use boron carbide as neutron absorbed material except for the automatic control rod, which uses stainless steel. A detailed description of the control rods is

given in [31]. The main areas of application of the reactor are associated with fundamental nuclear physics and materials science research, testing of structural and functional materials for fission and fusion reactors [32], as well as for the production of radioisotopes for medicine and industry [33].

The existing core of the WWR-K reactor consists of 28 fuel assemblies and 46 beryllium blocks (see Figure 1). Three high-flux irradiation positions are located in the center of the core. The inner diameter of regular irradiation ampoules is 50 mm. It is proposed to replace three irradiation positions and four fuel assemblies with a neutron trap which have an inner cavity 140 mm in diameter. Several fuel assemblies are loaded at the periphery of the core to compensate for the working reactivity margin. The final configuration of the core of the WWR-K reactor with a neutron trap is shown in Figure 2. The new core consist of 36 fuel assemblies, 1 beryllium trap and 33 aluminum displacers. The neutron trap is made of beryllium, which reduces neutron leakage from its lateral surface. All fuel assemblies in the new core configuration under consideration are fresh, i.e. without burnup of uranium fuel. Beryllium in the calculations was taken as fresh, i.e. not poisoned. The boundaries conditions used in the computational simulation are shown in Table 1. In the simulation, it was considered 500 cycles made of 50 in active and 450 active cycles with 200,000 histories per cycle.

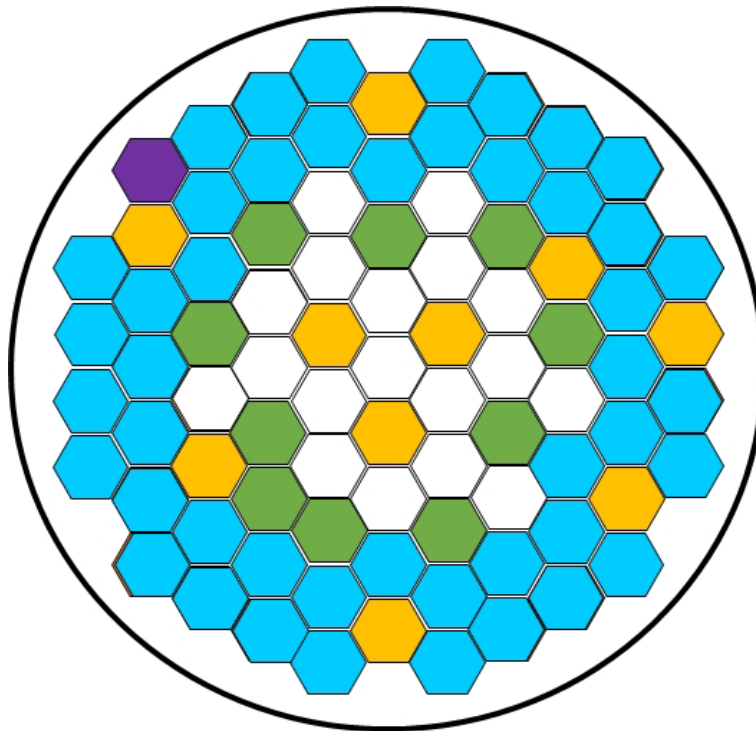


Figure 1. The existing core of the WWR-K reactor.

The following color designations are used in the Figures 1 and 2: white – fuel assembly, blue – beryllium block, yellow – irradiation position, green – fuel assembly with control rod, violet – empty cell, light green – aluminum displacer. Aluminum displacers are designed to form a water side neutron reflector and have an external size similar to the size of a fuel assembly.

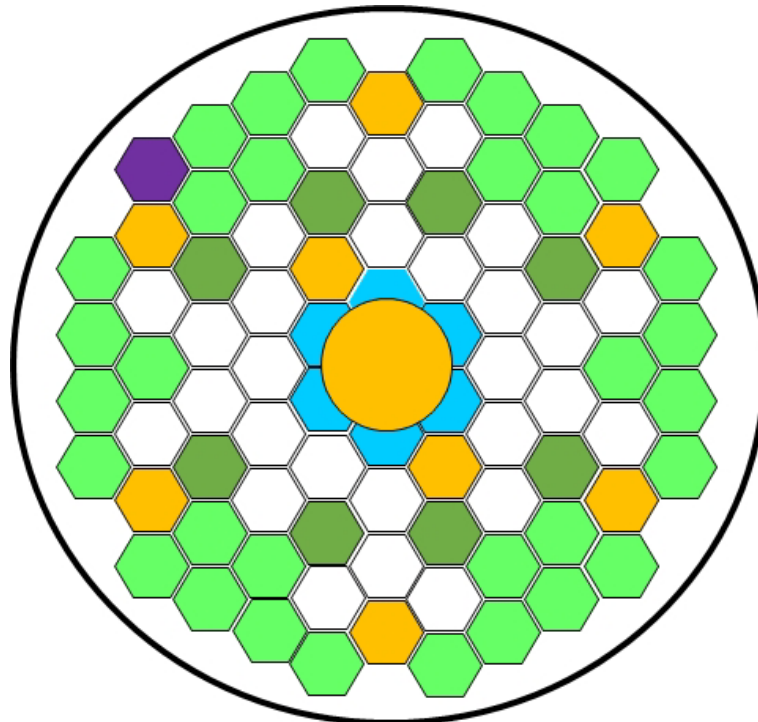


Figure 2. The core of the WWR-K reactor with a neutron trap.

Table 1.

The boundaries condition.

Parameter	Value
Temperature of coolant/moderator	300 K
Temperature of fuel	300 K
Density of boron carbide	1.76 g/cm ³
Density of beryllium	1.89 g/cm ³
Density of aluminum	2.70 g/cm ³
Pressure in core	atmosphere
Dimensions of neutron-multiplying medium	bounded dimensions

Results and discussion

The existing configuration of the WWR-K reactor core consists of 28 fuel assemblies and an annular beryllium neutron reflector. The nominal operational reactivity margin of the core is $5.0\% \Delta k/k$. This reactivity margin is sufficient to operate the reactor for 21 days, taking into account the irradiation work of different materials.

The considered new configuration of the WWR-K reactor core with a neutron trap consists of 36 fuel assemblies and an annular water neutron reflector. It also reduced the number of control rods from 10 to 8. The calculated reactivity margin of this configuration of the core is $(4.86 \pm 0.04)\% \Delta k/k$. The neutron-physical characteristics of irradiation positions in the WWR-K reactor core, without and with a neutron trap, are shown in Table 2. In the table given thermal neutrons

with an energy of less than 0.625 eV and fast neutrons with an energy of more than 0.1 MeV.

Table 2.

Characteristics of the irradiation positions of the WWR-K reactor ($\text{cm}^{-2}\text{s}^{-1}$).

Neutron energy	Neutron flux for EC	Neutron flux for NC
Thermal neutrons in CC	$1.9 \cdot 10^{14}$	$1.7 \cdot 10^{14}$
Fast neutrons in CC	$7.2 \cdot 10^{13}$	$2.1 \cdot 10^{13}$
Thermal neutrons in CP	$6.8 \cdot 10^{13}$	$6.3 \cdot 10^{13}$
Fast neutrons in CP	$1.1 \cdot 10^{13}$	$2.2 \cdot 10^{12}$

Note: CC – core center, CP – core periphery, EC – existing core, NC – new core with neutron trap.

Table 2 shows that in a neutron trap the thermal neutron flux decreases by 12% and fast neutron fluxes decrease 3 times compared to the existing configuration of the core, but the useful volume increases. The simulation results showed that the energy spectrum of neutrons in the trap has become softer (see table 3). The fraction of thermal neutrons in the integral neutron flux increased by 16%. However, at the periphery of the core, the fraction of thermal neutrons decreased by 12%. This is due to the use of a water annular neutron reflector in the new configuration of the core. As the fuel burnup, it will be possible to load beryllium blocks into the core to form an annular beryllium reflector and increase the fraction of thermal neutrons.

It should be noted that the two-irradiation positions near (bordering) the neutron trap have a competitive neutron flux. The flux of thermal neutrons in these positions is $1.3 \cdot 10^{14} \text{ cm}^{-2}\text{s}^{-1}$, and of fast neutrons - $4.4 \cdot 10^{14} \text{ cm}^{-2}\text{s}^{-1}$.

Table 3.

Thermal neutrons fraction in considered cores (%).

Irradiation position	EC	NC
CC	73	89
CP	86	74

In the new configuration of the core, the number of control rods decreased, but their efficiency is sufficient (see Table 4) to create an operational reactivity margin of $4.8\% \Delta k/k$. This reactivity margin is regular and is sufficient for an irradiation cycle lasting 21 days. The following designations are adopted in Table 4: AZ – emergency protection rod, KO – reactivity compensation rod, AR – automatic control rod. According to the nuclear safety rules requirements, the efficiency of the reactivity compensation rods and automatic control rod should be at least $1\% \Delta k/k$ higher than the reactivity margin, which is satisfied in the new configuration of the core. Also, according to the rules, the efficiency of the emergency protection rods group minus the most efficient emergency protection rod should be more than one delayed neutron fraction, which is also satisfied in the new configuration of the core. A small possible initial reactivity margin, of course, limits the experimental capabilities of the reactor in terms of irradiating materials that introduce significant negative reactivity. Therefore, to increase the

experimental capabilities of the reactor, it is necessary to consider the possibility of increasing the efficiency of the control rods for core with the neutron trap. In particular, annular control rods can be considered to replace existing ones.

Table 4.

Efficiency of the control rods ($\% \Delta k/k$).

Type of control rod	EC	NC
AZ1	1.52	1.14
AZ2	1.47	1.12
AZ3	1.42	1.19
ΣAZ	4.41	3.45
KO1	1.38	1.65
KO2	2.59	1.26
KO3	2.23	1.75
KO4	1.92	1.16
KO5	1.70	-
KO6	2.32	-
ΣKO	12.14	5.82
AR	0.32	0.46

An increase in the radial dimensions of the core leads to a decrease in the specific energy release in the fuel assembly. The maximum power release in a fuel assembly for a new core configuration is 229 kW, while for an existing core the maximum power release in a fuel assembly is 292 kW (see Table 5). The new core is less energy intensive. The energy release in the most energetically stressed fuel assembly is 28% less. Figure 3 shows the distribution of energy release over the core diameter.

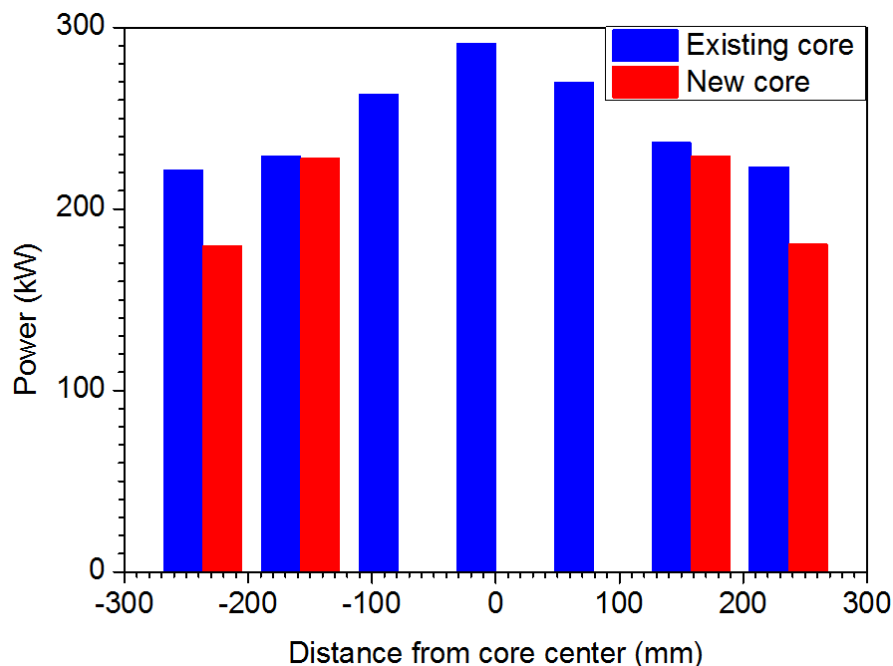


Figure 3. Distribution of energy release in fuel assemblies along the core diameter.

Table 5.

Power release in fuel assemblies (kW).

Cell	EC	NC	Cell (cont.)	EC (cont.)	NC (cont.)
5-2	-	168.0 \pm 0.2	5-8	-	179.1 \pm 0.1
3-2	-	143.5 \pm 0.1	8-7	223.2 \pm 0.3	165.8 \pm 0.1
5-3	221.8 \pm 0.3	179.8 \pm 0.1	7-8	-	180.7 \pm 0.1
4-3	-	163.7 \pm 0.1	9-7	-	146.1 \pm 0.1
7-3	-	181.5 \pm 0.1	7-9	-	168.4 \pm 0.2
6-3	-	201.9 \pm 0.2	6-5	291.6 \pm 0.4	-
5-4	229.0 \pm 0.4	227.9 \pm 0.2	7-6	269.9 \pm 0.4	-
4-4	224.3 \pm 0.3	205.9 \pm 0.2	6-4	263.2 \pm 0.4	-
3-4	-	177.1 \pm 0.1	5-6	264.4 \pm 0.4	-
9-2	-	137.9 \pm 0.1	4-5	234.8 \pm 0.4	-
7-4	238.2 \pm 0.4	216.9 \pm 0.2	8-5	253.9 \pm 0.4	-
2-5	-	137.4 \pm 0.1	4-7	232.0 \pm 0.4	-
9-3	222.3 \pm 0.3	134.0 \pm 0.1	1AZ	210.5 \pm 0.3	163.3 \pm 0.1
8-4	233.1 \pm 0.3	209.7 \pm 0.2	2AZ	214.5 \pm 0.3	162.8 \pm 0.1
4-6	-	201.1 \pm 0.2	3AZ	223.5 \pm 0.3	166.7 \pm 0.1
3-6	-	126.9 \pm 0.1	1KO	166.0 \pm 0.3	98.0 \pm 0.1
10-3	-	146.7 \pm 0.1	2KO	175.9 \pm 0.3	97.7 \pm 0.1
5-7	242.6 \pm 0.4	213.5 \pm 0.2	3KO	173.2 \pm 0.3	100.9 \pm 0.1
3-7	-	133.1 \pm 0.1	4KO	182.4 \pm 0.3	95.3 \pm 0.1
9-5	-	186.1 \pm 0.1	5KO	168.6 \pm 0.3	-
8-6	-	210.6 \pm 0.2	6KO	181.1 \pm 0.3	-
7-7	236.6 \pm 0.4	229.5 \pm 0.2	AR	172.1 \pm 0.3	142.0 \pm 0.1
6-7	251.4 \pm 0.4	200.7 \pm 0.2	-	-	-

It can be seen from the diagram shown in Figure 3 that there is a large difference in the energy release in the fuel assembly in the peripheral part of the core at the fuel-reflector interface when comparing the existing configuration of the core with the new one. The energy release decreases by (3-6)% for the existing configuration of the core, while for the new configuration, the decrease occurs by 27%. This behavior is explained by different annular reflectors in the considered configurations of the core, in the existing one – beryllium, in the new – light water.

From the point of view of thermophysical safety, the new configuration of the core can be considered safer, since the energy release in the fuel assembly is lower. Of course, the thermophysical safety of such a configuration needs to be considered in more detail. The calculation results given in this article will serve as the initial data for thermophysical analysis.

Conclusions

Computational analysis showed that in the center of the WWR-K reactor core it is possible to create a neutron trap with a competitive neutron flux. In a neutron

trap, it will be possible to irradiate objects up to 140 mm in diameter, which of course makes this irradiation position attractive. The maximum neutron flux in the neutron trap is 12% less than in the standard central irradiation position in the existing core, but the fraction of thermal neutrons in the integral neutron flux increases by 16%. The neutron flux at the peripheral irradiation positions remained practically unchanged.

The efficiency of control rods in the new configuration of the core meets the requirements of regulatory and technical documents.

The new core is less energy intensive. The power release in the most energetically stressed fuel assembly is 28% less than in the existing core.

To understand the prospects of such a configuration of the WWR-K reactor core, it is necessary to analyze its thermophysical safety.

Acknowledgments

This research is funded by the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan (Grant No. BR10965174).

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