Monte Carlo Calculation of Core Reactivity and Fluxes for the Development of the BNCT Neutron Source at the Kyiv Research Reactor

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Abstract. The presented results show our consecutive steps in developing a neutron source with parameters required by Boron Neutron Capture Therapy (BNCT) at the Kyiv Research Reactor (KRR) [1-4]. The main goal of this work was to analyze the influence of installation of different types of uranium converters close to the reactor core on neutron beam characteristics and on level of reactor safety. The general Monte Carlo radiation transport code MCNP, version 4B [5], has been used for these calculations.

INTRODUCTION

The WWR-M Kyiv Research Reactor (KRR) is a light-water moderated and cooled tank-type reactor with a beryllium reflector. The reactor currently uses 36% enriched uranium-235 WWR-M2 fuel assemblies, each of which consists of an outer hexagonal tube and two inner cylindrical tubes. The nominal thermal power is 10 MW. Today the KRR is used for various purposes, including neutron physics, materials research, radioisotope production, neutron transmutation doping of silicon, and other applications. One of the ten horizontal tubes is a thermal column (TC) with a graphite moderator. In accordance with preliminary calculations [1-4] this tenth horizontal channel could be transformed into an epithermal neutron source with parameters that meet the requirements of BNCT by replacing the graphite blocks with new moderators, filters, collimators, and shielding. The addition of a uranium converter can improve the parameters of the neutron beam. The purpose of our Monte Carlo calculations was to show that replacement of the graphite blocks in the thermal column with new moderators, reflectors, and filters and also installation of a uranium converter close to the reactor core does not reduce the safety of the KRR and to estimate an expediency of the uranium converter installation at the KRR.

MATERIALS AND METHODS

Our preliminary calculations [1-4] have shown that the best neutron beam parameters that can be obtained at the KRR without installation of an additional converter may be reached if we use for our tenth horizontal channel the following configuration and material components: 1) a Fluental or Al+CF_2 moderator, 50-60 cm long in the beam direction, arranged abutting the thermal column bottom with each side confined by a divergent natural nickel conical reflector; 2) a 274-cm-long convergent conical borated polyethylene collimator, coated on the inside with a 3.152-cm layer of natural nickel, which constricts the beam from 108 cm in diameter (at the moderator surface) to an outlet diameter of 4 cm (at the position of a potential patient); and 3) a 4-6-cm-long nickel-60 filter located close to the beam outlet. This configuration was taken as the base for all our calculations, the results of which are presented in this paper.

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The Monte Carlo calculation model of the reactor takes into account almost all of the KRR details, including the reactor tank, the hexagonal core geometry (about 220 WWR-M2 fuel assemblies, eight control- and safety-rods, a regulating rod, and peripheral beryllium assemblies), vertical irradiation channels, the thermal/epithermal column, reflectors, etc. (see Fig. 1), but to reduce the necessary computing time to a reasonable value, the calculations of neutron beam characteristics depending on different types of uranium converters were carried out using a simplified model, i.e., the neutron source was simulated as a surface source at the inner side of the beryllium core reflector with a neutron energy spectrum divided into three intervals: Maxwellian thermal spectrum, "1/E" slowing-down spectrum, and fission spectrum. This simplified model was described in detail in [3-4].

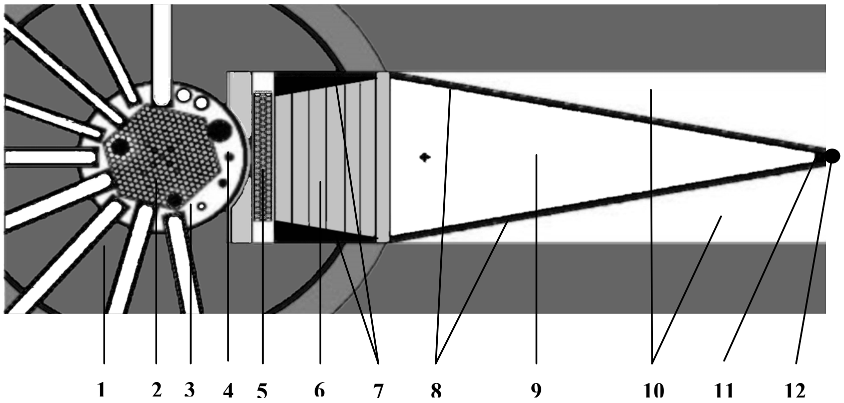

FIGURE 1. Geometry for the MCNP calculations (horizontal cross section through the core center). 1 - water, 2 - core, 3 - beryllium reflector, 4 - vertical channel, 5 - converter, 6 - moderator, 7 - reflector (natural nickel), 8 - natural nickel layer, 9 - air, 10 - borated polyethylene, 11 - nickel-60 filter, 12 - detector (the patient position).

The idea of using of a uranium converter to increase the epithermal neutron flux intensity was proposed in [6], and it was successfully realized at MITR [7]. We considered four main types of uranium converters, which can be mounted at the KRR from the point of view of the existing construction detail of the TC. The first type of uranium converter was a single fresh fuel assembly (mass of ^{235}U 37.0 g), inserted into the vertical channel passing through the beryllium reflector and cross axis to the TC (in Fig. 1 this channel is marked by number four). The second type of uranium converter considered consisted of one row of fuel assemblies (23 units) put in an aluminum container filled with H_2O. This converter is located inside the thermal column at a distance of 57.7 cm from the center of the reactor core. The total mass of ^{235}U is 851 g. The MCNP calculations for this converter have been carried out for two cases: the aluminum container filled with H_2O and D_2O. The third type of uranium converter consisted of three rows of fuel assemblies (67 units) put in an aluminum container (this type of converter is shown in Fig. 1). The total mass of ^{235}U is 2479 g. The fourth type of converter was simulated as a uranium plate in an aluminum matrix. Enrichment of ^{235}U is 30%, and the total mass of ^{235}U is 5000 g. The results obtained are presented in Table 1.

Energy ranges for epithermal and fast neutrons were taken as 1 eV – 20 keV and 20 keV –20 MeV, respectively. Dose computations were fulfilled without any biological bodies inside the model geometry. Fast

TABLE 1. MCNP calculation results without converter and with different types of uranium converters.

Type of Converter	Total mass of ^{235}U	Epithermal Flux, n/cm^{2}s	Epi / Fast Flux Ratio	Fast n Dose / Epithermal Flux, Gy$*$cm^2	Gamma Dose / Epithermal Flux, Gy$*$cm^2
none	0	$(2.00\pm0.04)10^{9}$	146 ± 20	$(1.35\pm0.18)10^{-13}$	$(2.29\pm0.19)10^{-12}$
I	37 g	$(2.72\pm0.15)10^{9}$	142 ± 30	$(1.27\pm0.24)10^{-13}$	$(1.82\pm0.20)10^{-12}$
II (H_2O)	851 g	$(4.10\pm0.30)10^{9}$	50 ± 5	$(4.03\pm0.61)10^{-13}$	$(2.52\pm0.28)10^{-12}$
II (D_2O)	851 g	$(4.83\pm0.33)10^{9}$	54 ± 6	$(2.23\pm0.40)10^{-13}$	$(2.42\pm0.52)10^{-12}$
III	2479 g	$(1.44\pm0.03)10^{10}$	70 ± 5	$(1.87\pm0.82)10^{-13}$	$(4.02\pm1.10)10^{-13}$
IV	5000 g	$(1.54\pm0.03)10^{10}$	101 ± 7		

neutron and gamma-ray dose rates per unit epithermal neutron flux, given in the fifth and sixth columns of Table 1, were calculated in parallel with flux calculations by modification of the detector tally with flux-to-dose rate conversion factors. The meaning of these factors for biological tissue was taken from American National Standard ANSI/ANS-6.1.1-1977, cited in [5]. As shown in Table 1, insertion of a uranium converter allows an increase in the epithermal neutron flux intensity of seven times for the three-rowed converter with 67 fuel assemblies (Case III). In this case the epithermal neutron flux intensity becomes (1.44 ± 0.03)10^{10} n/cm^2s with a ratio of epithermal to fast neutron flux of 70 ± 5. Table 1 also shows that using D_2O as a converter coolant improves the epithermal neutron beam parameters rather inconsequentially – the epithermal flux increases only 7% compared to H_2O; therefore H_2O is more preferable in our case, since light water is the core coolant at the KRR.

It is obvious, however, that being placed close to the reactor core, the converter may influence the safety of the reactor. To check how the converter affects the effective multiplication factor, k_{eff}, we have carried out two sets of calculations with MCNP to simulate cases with and without a converter installed. In our calculations we have used the actual core load, which reflects the level of fuel burnup for each fuel assembly. The core load used for calculations is presented in Fig. 2. In this figure numbers give the mass loss of ^{235}U in percent. The content of isotopes produced has been estimated using the ORIGEN2 code [8]. Table 2 gives the comparison of the mass content of the isotopes for the cases of fresh fuel and the most burned one (about 65%) used in the core load. The second column of Table 2 includes the isotopes from fresh fuel and the produced isotopes that are the most important ones in the sense of the effect on the neutron flux. To estimate the maximum possible changes in reactivity, we performed calculations for two different positions of the regulating rod and the five shim rods, that is, for a working regime and for the case of both regulating and shim rods at the top. The working regime of the reactor corresponds to the regulating rod being 31 cm withdrawn, four shim rods at the bottom and one 30 cm withdrawn. Results obtained in the two sets of calculations described above are summarized in Table 3. The first row of this table shows k_{eff} for the working regime of the reactor, and the second row gives the change in reactivity for the regulating and shim rods at the top with respect to their positions in the working regime. It is seen that the increase in k_{eff} as the converter is installed is quite small and does not destroy the safety of the reactor.

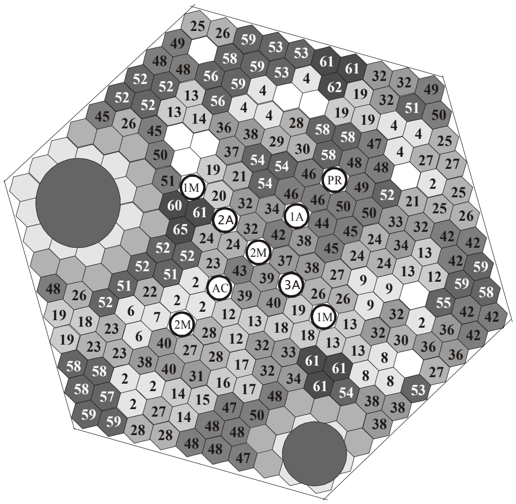

FIGURE 2. The core load used for the MCNP calculations.

TABLE 2. The mass content of isotopes for the fresh fuel compared to the mass content of isotopes for fuel having a burn level of about 65%.

Burn Level	Isotope	Mass Content, grams
Fresh Fuel	^{235}U	37.0
	^{238}U	65.8
	^{27}Al	210.1
	^{16}O	13.9
Burned Fuel (65%)	^{235}U	12.5
	^{238}U	64.1
	^{27}Al	210.1
	^{16}O	13.9
	^{236}U	3.8
	^{239}Pu	0.6
	^{240}Pu	0.2
	^{143}Nd	0.5
	^{149}Sm	$1.3\cdot10^{-3}$
	^{145}Xe	$9.7\cdot10^{-5}$

TABLE 3. Calculation results for the effective multiplication factor in the cases with and without converter installed.

	Converter Installed	No Converter
k_{eff}	1.0387 ± 0.0003	1.0367 ± 0.0003
Δk/k, %	6.1	6.3

One should note that the values of k_{eff} obtained are different from the value of 1.001 given by regulatory procedure codes used in the technical support at KRR. This deviation appears due to the fact that our results do not take into account the actual ^{235}U density distribution along the non-fresh fuel assembly. We have assumed uniform distribution while the actual one should give a smaller density of ^{235}U at the central part of the assembly with an increase in density toward the periphery [9].

The calculation results obtained show that the three-layered uranium converter allows an increase in the epithermal neutron flux of seven times without a decrease in a level of reactor safety. However, even employment of this converter does not allow the epithermal neutron beam parameters to completely satisfy BNCT requirements. So, as shown in Table 1, the specific photon dose D_γ/ϕ_{epi} exceeds the admissible value by a factor of about two. As a rule, to reduce the photon dose shields of Bi, Cd, Pb, etc. are applied. An MCNP calculation with different shields has been conducted. The influence of these shields on the neutron beam parameters can be seen in Table 4, where the calculated results are presented in the form of relative values (with/without shield).

TABLE 4. The MCNP calculation results without and with different type of shields.

Type of Shield	Epi	Epi/ Fast	Dose Fast/Epi	Dose γ/Epi
none	1	1	1	1
Bi 80 mm	0.66	1.4	0.66	0.46
^{10}B 0.923 mm	0.50	0.6	1.7	2.6
Cd 0.5 mm	1.0	0.89	1.2	0.93
Bi +^{10}B+ Cd	0.32	0.45	2.0	1.23
Pb (80 mm) +^{10}B+ Cd	0.26	0.58	1.7	1.29
Bi (at the outlet) +^{10}B+ Cd	0.16	0.7	1.6	0.34

So, the best result could be obtained by using an 8-cm Bi shield; the photon dose ratio (D_γ /ϕ_{epi}) becomes less than $2x10^{-13}$ Gy∗cm^2, although the epithermal neutron flux intensity also diminishes by a factor of 1.5, with the rest of the parameters taking a turn for the better.

Another way that may be used to improve the parameters of the neutron beam is changing part of the beryllium reflector in the TC area to Al and using an aluminum-polytetrafluoroethylene moderator instead a fluental one. MCNP calculations for a moderator consisting of 13 cm CF_2 and 63.7 cm Al have shown that replacing beryllium with a part of the aluminum component (17.35 cm) allows an increase of a factor of eleven in the epithermal flux intensity with other beam parameters also being satisfactory and able to be improved by using special shields. The development of this arrangement will be continued in future investigations.

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