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NEUTRON SPECTRA AND FLUXES IN HORIZONTAL CHANNELS OF RESEARCH REACTOR WWR-M WHILE CONVERSION ON LOW-ENRICHED FUEL

Neutron fluxes and spectra in the horizontal experimental channels of reactor WWR-M of the Institute for Nuclear Research, National Academy of Sciences of Ukraine (Kyiv) have been calculated using neutron transport Monte Carlo model with fuel enriched in ^{235}U both to 36 and 19.7 %. It is shown that at the very beginning operating with low-enriched fuel, when the reactor core is 28 % filled with "fresh" fuel assemblies, and the remaining cells are filled with beryllium displacers, there is a significant change in the parameters of neutron beams. However, after the reactor will begin to operate at its usual mode, that will be after completing all or most part of the core with fuel assemblies partially burnt out, spectra and fluxes in channels will restore most of their previous values. Some differences are mainly due to changes in composition of the core – the removal of two voluminous vertical water channels located within the core. The work can be helpful to experimenters working with extracted beams at this reactor and so at other reactors that have been converted to low-enriched fuel.

Keywords: nuclear research reactor, neutron spectra, neutron fluxes, horizontal experimental channels, Monte Carlo calculation.

Introduction

Kyiv research reactor of the Institute for Nuclear Research WWR-M is a basin type thermal reactor with beryllium reflector and with water both as a moderator and a coolant. Its core has a hexagonal prism shape and consists of 271 cells, in 6 of which rods of the reactor power control are placed, in 3 cells – all-stop channels. The core is formed of the fuel assemblies M2, each of which consists of three concentric tubular fuel elements. Nuclear fuel in fuel elements is uranium dioxide, enriched in ^{235}U, in an aluminum matrix. Mass of ^{235}U in a single fuel assembly is 37 g.

The reactor has 17 vertical channels for irradiation of materials, 13 of them located in the reflector and 4 in the thermal column (TC). Also, there are 10 radial horizontal channels (HEC) for experiments with extracted beams. 3 of them (HEC-6, 7 and 8) have an inner diameter of 60 mm, 1 – (HEC-TC) 120 mm, the other six – 100 mm.

Fuel assemblies used until 2011 had enrichment of 36 %. In 2011, in connection with the obligations taken by Ukraine, the reactor was converted to low-enriched fuel – 19.7 %.

This work aims to study the fluxes and spectra of neutrons at the outlets of horizontal channels after conversion to low-enriched reactor fuel.

Research method

Neutron spectra and fluxes were determined by calculating with method of statistical testing (Monte Carlo) using the program MCNP [1] and a mathematical model of the Kiev research reactor [2] which took into account its structure in detail according to technical documentation: fuel assemblies, Beryllium reflector, horizontal and vertical experimental channels, the pool, thermal column and so on. All fuel assemblies actually had different burn-up of ^{235}U, but in the calculations the burn-up was assumed to be the same. Also it was taken into account accumulation of ^{3}He and ^{6}Li in the Beryllium reflector due to reactions under action of neutrons during previous work of the reactor.

Density of neutron flux and spectrum in a horizontal channel of the reactor depends mainly on the following factors.

1. Channel diameter. Flux density is proportional to the square of the diameter.
2. The location of the bottom of a channel with respect to Be reflector: channels can penetrate through the entire reflector (HEC-2, 4, 7, 9), only through a portion of its thickness (HEC-1, 3, 5, 6, 8) or originate from the outer surface of the reflector (horizontal channel in the thermal column). General rule is: the deeper the channel penetrates through the reflector, the higher the portion of fast neutrons.
3. Initial fuel enrichment in ^{235}U and the degree of burnout.
4. The presence or absence of irradiation channels in the core.
5. Filling the core with fuel assemblies, i.e. the ratio between the number of fuel assemblies and beryllium displacers.

It was supposed that all horizontal channels are empty: no collimators, filters and mechanisms inside them.

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Results

The beam parameters at 3 compositions of the core are investigated in this work.

Neutron spectra and fluxes have been calculated at the outlets of all HECs on axes of beams 5 cm from the biological shielding of the reactor at the compositions A, B and C (Fig. 1).

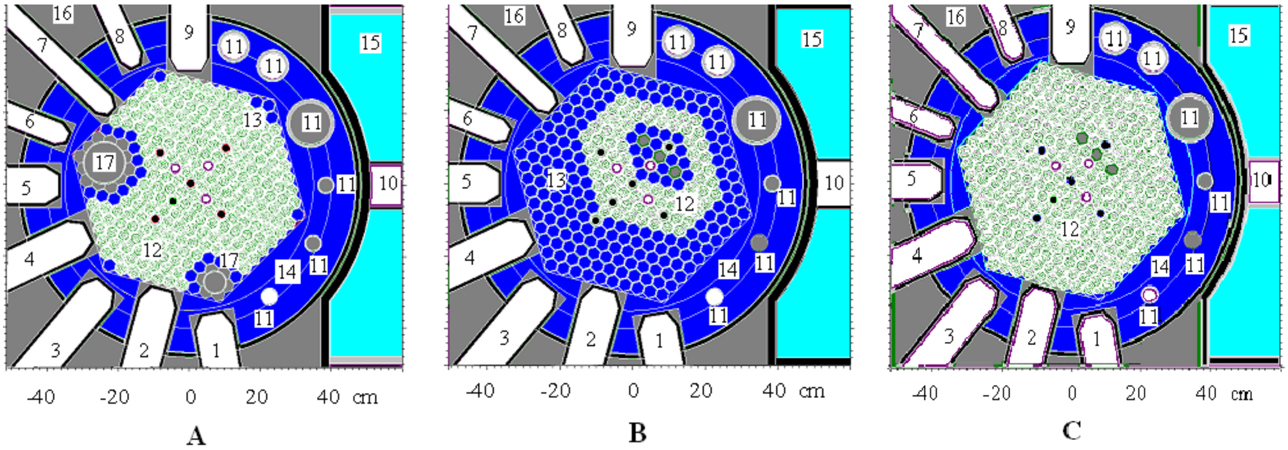

Fig. 1. Compositions of the core (computer model): A – before converting the reactor on low-enriched fuel, initial enrichment is 36 %, burn-up 39.7 %; B – the core after conversion on low-enriched fuel, initial enrichment 19.7 %, burn-up 0 %; C – after replacing all beryllium displacers with fuel assemblies, initial enrichment 19.7 %, burn-up 50 %. *1 - 9* – horizontal channels HEC-1 ÷ HEC-9; *10* – horizontal channel in thermal column; *11* – vertical channels; *12* – fuel assemblies; *13* – beryllium displacers; *14* – beryllium reflector; *15* – graphite of thermal column; *16* – water in the reactor pool; *17* – vertical irradiation channels. ● – control rods; ○ – all-stop channels; ● – cells for vertical channels inside the core.

We can see that spectra in all channels at all compositions consist of three parts (Fig. 2, *a - j*): a low-energy peak from 0.001 to 0.5 eV (thermal spectrum with the Maxwell distribution), high-energy peak from 56 to 20 MeV (fission neutron spectrum, partially deformed by moderation) and a horizontal section between the peaks (moderation spectrum 1/E). Shapes of the spectra are similar one to another and are typical for thermal reactors. The differences lie in the ratios between flux densities at each of the three parts (Table and Fig. 2, *a - j*) which are due to the above factors 1 - 5. We consider the peculiarities in each of these three compositions separately.

Composition A – it existed before conversion to a new fuel (see Fig. 1, A). Initial enrichment of fuel elements is 36 %. The burn-up in the calculations was assumed to be 39.7 % (this value was obtained by calculations from the condition $K_{eff} = 1$ when the lower ends of the control rods are set at the height of the core center). Besides, six beryllium displacers and two vertical irradiation channels filled with water and screened off from fuel assemblies with 18 beryllium displacers are placed in the core.

Fluxes, especially epithermal, in HEC-1 and HEC-6 are relatively low (Fig. 3, A, Table). Explanation: the channels are separated from fuel assemblies with two vertical irradiation water channels (see Fig. 1, A). Besides, HEC-6 has a smaller diameter.

To a lesser degree, these factors become apparent in HEC-5 and HEC-7.

Most hard spectra (highest percentage of fast neutrons) are in channels that "look" immediately into the core: HEC-2, 4, 7, 9. Softest spectrum is in the horizontal channel of the thermal column.

Composition B – this loading corresponds to the beginning of operation on low-enriched fuel (see Fig. 1, B). Fuel assemblies have enrichment 19.7 %, all of them are "fresh" (burn-up 0 %). Both irradiation channels have been extracted from the core. 72 fuel assemblies (in terms of single ones) were placed in the core. The remaining 187 cells are filled with beryllium displacers to compensate excess reactivity.

Total fluxes in channels HEC-1÷HEC-4 and TC fell 1.5÷4 times in comparison with composition A (see Fig. 3, A and B). At the same time, total fluxes in channels HEC-5 and 8 have not changed and in HEC-6, 7 and 9 increased, respectively, by 1.7, 1.4 and 1.15 times. Fluxes of epi-thermal and fast neutrons slumped in the most of horizontal channels (respectively, HEC-1 – 2.5 and 3, HEC-2 – 6 and 9, HEC-3 – 11 and 14, HEC-4 – 6 and 9, HEC-8 – 1.4 and 2 times, HEC-5 and HEC-TC – twice). Such changes can be mainly attributed to two factors:

asymmetry placing fuel assemblies in the core (see Fig. 1, B) – of all horizontal channels only HEC-9 is separated from assemblies with two layers of beryllium displacers, HEC-7 and 8 – with three layers, HEC-6 – from four to six, the others – six layers;

removal of both vertical irradiation channels.

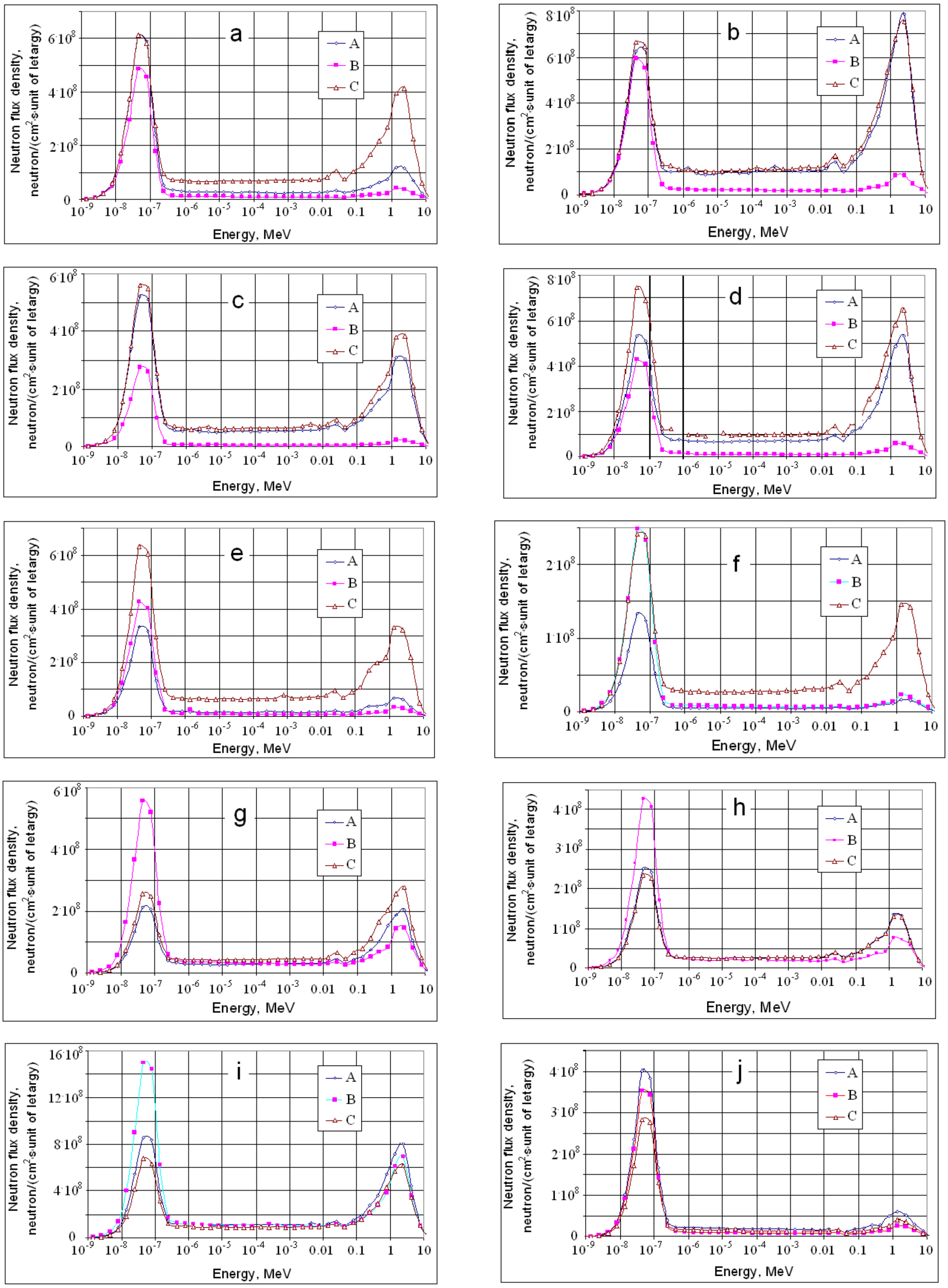

Fig. 2. Neutron spectra at outlets of horizontal channels: *a* – HEC-1; *b* – HEC-2; *c* – HEC-3; *d* – HEC-4; *e* – HEC-5; *f* – HEC-6; *g* – HEC-7; *h* – HEC-8; *i* – HEC-9; *j* – HEC-TC (in the thermal column). Compositions of the core: A – before converting the reactor on low-enriched fuel, initial enrichment is 36 %, burn-up 39.7 %; B – after conversion on low-enriched fuel, initial enrichment 19.7 %, burn-up 0 %; C – after replacing all beryllium displacers with fuel assemblies, initial enrichment 19.7 %, burn-up 50 %.

Neutron flux densities and their components at three compositions of the reactor core

Horizontal experimental channel	Loading the core (composition)	Total neutron flux density, 10^9·neutron/(cm^2·s)	Thermal neutron flux density (< 0.5 eV), 10^9·neutron/(cm^2·s)	Epithermal neutron flux density (0.5 eV - 0.05 MeV), 10^9·neutron/(cm^2·s)	Fast neutron flux density, (0.05 MeV - 20 MeV), 10^9·neutron/(cm^2·s)
HEC-1	A	1.85	1.22	0.298	0.329
	B	1.18	0.947	0.121	0.114
	C	3.20	1.28	0.811	1.11
HEC-2	A	4.43	1.36	1.16	1.90
	B	1.56	1.15	0.196	0.213
	C	4.73	1.45	1.28	2.00
HEC-3	A	2.58	1.11	0.632	0.837
	B	0.648	0.529	0.0584	0.061
	C	2.97	1.18	1.07	0.722
HEC-4	A	3.31	1.15	0.799	1.37
	B	1.12	0.839	0.129	0.153
	C	4.47	1.63	1.16	1.69
HEC-5	A	1.06	0.671	0.194	0.193
	B	1.03	0.837	0.105	0.0891
	C	3.06	1.32	0.779	0.960
HEC-6	A	0.360	0.262	0.0514	0.0469
	B	0.617	0.485	0.0717	0.0601
	C	1.24	0.512	0.322	0.406
HEC -7	A	1.33	0.458	0.340	0.535
	B	1.87	1.13	0.354	0.382
	C	1.82	0.559	0.498	0.759
HEC-8	A	1.20	0.528	0.302	0.368
	B	1.24	0.834	0.212	0.191
	C	1.16	0.491	0.303	0.361
HEC-9	A	5.15	1.84	1.28	2.03
	B	5.90	3.02	1.24	1.65
	C	4.05	1.42	1.02	1.61
HEC-TC	A	1.17	0.788	0.214	0.171
	B	0.863	0.687	0.105	0.0717
	C	0.876	0.572	0.190	0.113

Composition C – this loading corresponds to the state of the core after gradual replacement of beryllium displacers by fuel assemblies with initial enrichment of 19.7 % and burn-up of 50 % (see Fig. 1, C; with this burn-up $K_{eff} = 1$ when the lower ends of the control rods are set at the height of the core center). According to estimates, this download can be implemented after the reactor output will be about 85,000 megawatt-hours on low-enriched fuel.

In general, the spectra and the flux densities on the horizontal beams are similar to those that were when the reactor operated on highly-enriched fuel (see Figs. 2 and 3). Changes in the flux densities and its components in comparison with composition A are the following:

HEC-1. Thermal flux will be restored quite, epithermal and fast fluxes will increase threefold.

HEC-2 and 8. All components (thermal, epithermal and fast) will be restored.

HEC-3. Epi-thermal flux will increase by 69 %, fast flux will fall by 14 %.

HEC-4 and 7. All components of the fluxes will increase by about a third.

HEC-5. Thermal flux will be doubled, epithermal increase by four, fast – by five times.

HEC-6. Thermal flux will be doubled, epithermal increase by six times, fast – by eight times.

HEC-9. All components will decrease approximately by 20 %.

HEC-TC. The total flux will be reduced by a quarter (thermal – by 27%, epi-thermal – 11 %, fast – 34 %).

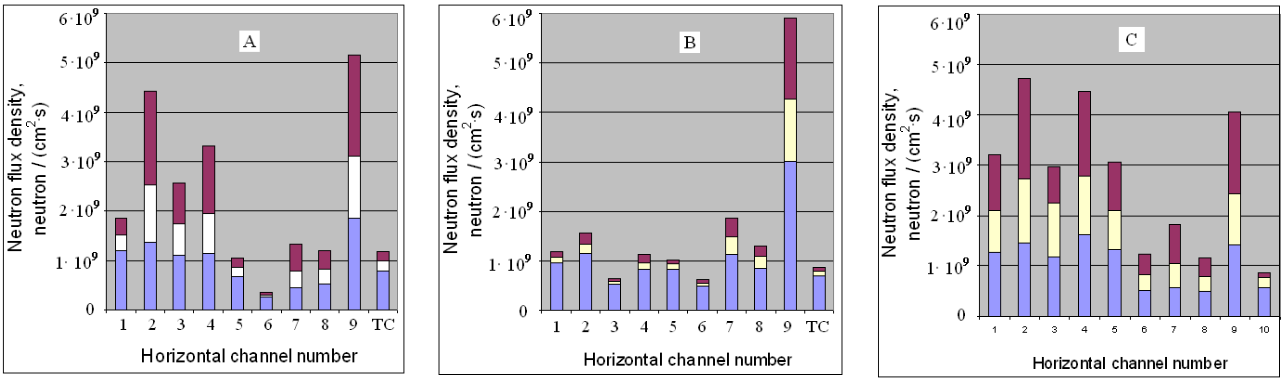

Fig. 3. Neutron flux densities and their constituents at the outlets of horizontal channels for the core compositions A, B and C: 🟦 – thermal flux density, ☐ – epy-thermal, 🟪 – fast.

Conclusion

It was shown by model calculations that conversion of the research reactor WWR-M from highly-enriched fuel (initial enrichment in ^{235}U 36 %) on the low-enriched (19.7 %) substantially modifies both neutron spectra and fluxes at the outlets of horizontal experimental channels. These changes are caused not so much with the transition to a different fuel as with the need to start a company with "fresh", i.e. unburned, fuel rods and with consequent need to fill the core with fuel assemblies only by 28 % to compensate the excess reactivity. Partially these changes are also associated with the removal of two large water cavities out of the core.

During the subsequent operation of the reactor, as fuel will be burned out, beryllium displacers in the core will be replaced by fuel assemblies. After full filling the core parameters of neutron beams will be close to those which were before conversion to a new fuel. The remaining differences are mainly due to the absence of water cavities in the core.

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СПЕКТРИ І ПОТОКИ НЕЙТРОНІВ У ГОРИЗОНТАЛЬНИХ КАНАЛАХ ДОСЛІДНИЦЬКОГО РЕАКТОРА ВВР-М ПРИ ПЕРЕХОДІ НА НИЗЬКОЗБАГАЧЕНЕ ПАЛИВО

Розраховано потоки та спектри нейтронів у горизонтальних експериментальних каналах реактора ВВР-М Інституту ядерних досліджень НАН України (Київ) з використанням Монте-Карло моделі транспорту нейтронів зі збагаченням по ^{235}U 36 і 19,7 %. Показано, що на самому початку роботи на низькозбагаченому паливі, коли активна зона реактора заповнена лише на 28 % “свіжими” паливними збірками, а решта комірок зони заповнена берилієвими витискувачами, має місце значна зміна параметрів нейтронних пучків. Але після того як реактор почне працювати у своєму звичайному режимі, що відбудеться після укомплектування всієї або більшої частини активної зони паливними збірками, які частково вигоріли, спектри і потоки в каналах відновлять свої попередні величини. Деякі різниці пов’язані головним чином зі змінами в композиції активної зони – вилученням двох об’ємних вертикальних водних каналів, розташованих у середині зони. Робота може бути корисною експериментаторам, які працюють на виведених пучках на цьому реакторі, а також на інших реакторах, що переведені на низькозбагачене паливо.

Ключові слова: дослідницький ядерний реактор, нейтронні спектри, нейтронні потоки, горизонтальні експериментальні канали, розрахунки Монте-Карло.

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СПЕКТРЫ И ПОТОКИ НЕЙТРОНОВ В ГОРИЗОНТАЛЬНЫХ КАНАЛАХ ИССЛЕДОВАТЕЛЬСКОГО РЕАКТОРА ВВР-М ПРИ ПЕРЕХОДЕ НА НИЗКООБОГАЩЕННОЕ ТОПЛИВО

Рассчитаны потоки и спектры нейтронов в горизонтальных экспериментальных каналах реактора ВВР-М Института ядерных исследований НАН Украины (Киев) с использованием Монте-Карло модели транспорта нейтронов с обогащением по ^{235}U 36 и 19,7 %. Показано, что в самом начале работы на низкообогащенном топливе, когда активная зона реактора заполнена только на 28 % „свежими” топливными сборками, а остальная часть ячеек зоны заполнена бериллиевыми вытеснителями, имеет место значительное изменение параметров нейтронных пучков. Однако после того как реактор начнет работать в своем обычном режиме, что произойдет после укомплектования всей или большей части активной зоны частично выгоревшими топливными сборками, спектры и потоки в каналах восстановят свои прежние величины. Некоторые различия связаны главным образом с изменениями в композиции активной зоны – извлечением двух объемных вертикальных водных каналов, размещенных внутри зоны. Работа может быть полезной экспериментаторам, работающим на выведенных пучках на этом реакторе, а также на других реакторах, переведенных на низкообогащенное топливо.

Ключевые слова: исследовательский ядерный реактор, нейтронные спектры, нейтронные потоки, горизонтальные экспериментальные каналы, расчеты Монте-Карло.

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