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COMPUTATIONAL STUDY OF RADIATION CHARACTERISTICS IN THE NICHE OF THE EXPERIMENTAL DEVICES OF THE WWR-K REACTOR

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A nuclear reactor is a complex engineering and technical installation that generates radiation. Because of this, the experimental measurement of the radiation characteristics of a nuclear reactor is a difficult task, and in some cases technically impossible. The modern development of calculation codes and tools makes it possible to determine the radiation characteristics of a nuclear reactor with sufficient accuracy and reliability. Due to this, computational modeling of physical processes occurring in a nuclear reactor has become one of the main scientific research methods. The WWR-K reactor is a multi-purpose research reactor with a large number of vertical and horizontal irradiation positions used for a wide range of scientific and applied problems. The irradiation position with the largest dimensions in the WWR-K reactor is the niche of experimental devices, which makes it possible to irradiate objects up to 1000 mm in diameter. This position is considered as a candidate for neutron transmutation doping of silicon ingots with a diameter of more than 200 mm. The article presents the radiation characteristics for the current and modernized configuration of the niche of the experimental devices of the WWR-K reactor. It is shown that the upgrade of the configuration leads to an improvement in the neutron characteristics in the irradiated position.

Keywords: *WWR-K, niche of the experimental devices. radiation characteristics, Neutron-transmutation-Doped Silicon (NTD-Si), Monte Carlo N-Particle Transport Code (MCNP)..*

INTRODUCTION

Currently, there is an active development of nuclear and radiation technologies around the world. The scope of such technologies is very wide. For example, the production of radioisotopes for medicine [1–6], radiation coloring of semiprecious stones for the jewelry industry [7–10], neutron transmutation doping of semiconductors for the electronics industry [11–14], and radiation treatment of seeds for the agricultural industry [15–17]. Nuclear and radiation technologies are implemented based on nuclear and electrophysical installations, in particular, on the basis of research reactors. The introduction and development of such technologies requires an accurate determination of the radiation characteristics of the reactor, which can be determined both experimentally and by calculation.

The modern development of computational methods and codes makes it possible to carry out sufficiently detailed and accurate calculations, which makes them one of the main scientific research methods. Particularly noteworthy are numerical simulation methods based on the Monte Carlo method, which make it possible to carry out precision calculations [18–20].

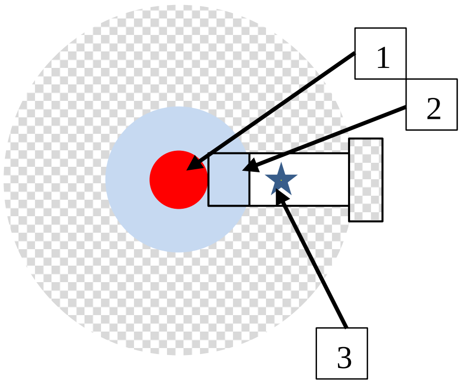
Earlier, R&D work was carried out based on the WWR-K reactor, together with Japanese companies, on neutron-transmutation doping of silicon ingots with a diameter of 6 inches (or 150 mm). Research was aimed at reducing the axial non-uniformity of doping silicon ingots. As a result, an axial non-uniformity doping of no more than 12% was obtained without the use of screen [21], and with the use of a screen, 4% [22, 23].

Nowadays, on the WWR-K reactor the possibility of carrying out neutron-transmutation doping of silicon ingots of large diameter (more than 200 mm) is being considered. For such a purpose, the reactor has only a single irradiation position – a niche of experimental devices. Preliminary studies of the radiation characteristics in the niche showed [24] that they do not comply with the IAEA recommendations for neutron transmutation doping of silicon [11]. Changes to the configuration and conditions at the given irradiation position are required. Proceeding from this, computational modeling of the niche of the experimental devices of the WWR-K research reactor was carried out and a change in the radiation characteristics was predicted when the niche configuration was modernized. The purpose of this work is to substantiate the possibility of creating the required conditions for irradiating large-diameter silicon ingots in the niche of the experimental devices of the WWR-K reactor.

MATERIALS AND METHODS

The niche of the experimental devices of the WWR-K reactor is a cylinder with a diameter more than one meter (Figure 1). In the niche there is a system of screens filled with water, which are mounted on a self-propelled trolley. The screens are designed to change the ratio of the gamma and neutron components of the reactor radiation field. The water screen system consists of three tanks that can be remotely filled or emptied. The tanks are installed between the core and the irradiated object.

WWR-K is a tank-type research reactor. The nominal power of the reactor is 6 MW. The coolant and moderator are demineralized water. The neutron reflector is demineralized water and beryllium. The maximum thermal neutron flux in the central irradiation positions of the core is $2\cdot10^{14}$ cm$^{-2}\cdot$s^{-1} [25, 26].



1 – core; 2 – water screens; 3 – irradiation position

Figure 1. Schematic view of the irradiation position

Computational modeling of physical processes in the WWR-K reactor in order to determine its radiation characteristics was carried out by the Monte Carlo method using the MCU-REA and MCNP6 codes [27, 28]. The MCU-REA code is designed to calculate the neutronic characteristics of nuclear reactors of various types. MCU-REA also allows the calculation of neutronic characteristics, taking into account changes in the isotopic composition of the materials of a nuclear reactor. The developer of the MCU-REA code is the Russian Research Center "Kurchatov Institute", Moscow, Russia. The program's firmware is made up of the DLC/MCUDAT-2.1 nuclear data bank. The calculation of the space-energy distribution of neutrons was carried out using the BNAB-98 library with a 26-group system of constants [29]. The MCNP6 transport code is intended for solving problems in the field of nuclear reactor physics, radiation protection, dosimetry, radiography, radiation medicine and nuclear safety. The user has the ability to model geometric three-dimensional configurations by setting the mathematical equations of the surfaces limiting them of the first, second and fourth degree, and filling them with an arbitrary material, setting the concentration of the nuclei of the elements that make up the substance. The ENDF/B-VII.1 library of cross sections for the interaction of neutrons with matter in the MCNP6 transport code was used [30]. In MCU-REA and MCNP6, the current configuration of the WWR-K reactor core was simulated with a real material composition. Due to the fact that the niche is located outside the core (in the concrete shield of the reactor), the control rods do not affect the distribution of the neutron field. Therefore, the calculations were carried out for the option when all control rods were removed from the core. The statistical error of calculations did not exceed 5%. The input file for all MCNP6 calculations included 200 cycles made of 20 inactive and 180 active cycles with 500,000 histories per cycle. The initial conditions used in the calculations are given in Table 1.

Table 1. Main initial conditions for physical calculations.

Parameter	Value
Temperature of moderator, K	293.6
Temperature of fuel, K	293.6
Density of B_4C, g/cm^3	1.76
Density of beryllium, g/cm^3	1.89
Density of aluminum, g/cm^3	2.70
Coolant temperature, K	293.6
Air temperature, K	293.6
Dimensions of neutron-multiplying medium	bounded dimensions

RESULTS AND DISCUSSION

According to [11], the main criteria for choosing an irradiation position for neutron transmutation doping of silicon are:

1. radial unevenness coefficient – 4–5% (may vary depending on customer requirements);
2. height coefficient of unevenness – 5–8% (may vary depending on the requirements of the customer);
3. irradiation accuracy < 3%;
4. the ratio of the flux of thermal neutrons to fast neutrons is 7:1;
5. cadmium ratio > 10;
6. gamma radiation flux – as low as possible;
7. ingot irradiation temperature < 180 °C.

From the above criteria, it can be seen that in the area of irradiation of silicon ingots, the neutron spectrum should be thermal. Due to the fact that fast neutrons create defects in the silicon lattice [11]. It should also be noted that the gamma radiation flux should be as low as possible in the irradiation position, since it is the main source of energy release.

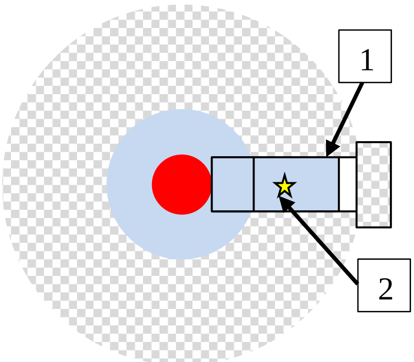
First of all, the radiation characteristics of the niche of experimental devices for the current configuration (see Figure 1) were determined in order to compare the criteria described above. The irradiation position is considered, loading into which is carried out through a vertical well (the distance to the central axis of the core is 1610 mm). The calculation results are shown in Table 2. The air environment in the irradiation position. Shielding screens are filled with water.

Table 2. Radiation characteristics in the niche of experimental devices

Characteristic	Value
Thermal neutron flux (< 0.465 eV), cm^{-2}s^{-1}	$1.1 \cdot 10^8$
Fast neutron (> 0.1 MeV), cm^{-2}s^{-1}	$2.7 \cdot 10^7$
Axial non-uniformity of thermal neutron flux (<0.465 eV), %	35
Thermal to fast neutrons ratio	4.1
Fraction of thermal neutrons in the integral flux, %	65
Gamma radiation flux (1 eV – 10.5 MeV), cm^{-2}s^{-1}	$1.5 \cdot 10^{11}$
Cadmium ratio	3.8

Table 2 shown that the radiation characteristics in the current configuration of the niche do not meet the above criteria. In particular, such characteristics as the ratio of the thermal to fast neutron flux and the cadmium ratio do not correspond; the neutron energy spectrum is not thermal enough. Therefore, it is necessary to reduce the neutron energy, which is possible when replacing the air environment to water in the irradiation position. Therefore, placement in a niche, of an aluminum tank filled by water was considered (Figure 2). The distance to the irradiation position does not change.

When the air environment is replaced by a water one in the niche of the experimental devices, the neutron energy spectrum more thermal (Table 3). The ratio of the thermal to fast neutron flux increases from 3.3 to 4.6. The energy spectrum of neutrons is divided into two groups: up to 1 keV and above 1 keV. Such a division into two energy groups is due to the fact that the capture cross section of silicon (^{30}Si) up to an energy of 1 keV corresponds to the 1/v law, and above 1 keV there is a region of resonances. Therefore, when doping silicon, it is necessary to take into account neutrons with energies up to 1 keV, and not only up to the cadmium boundary.



1 – additional tank with water; 2 – irradiation position

Figure 2. Schematic view of the irradiation position

Table 3. Neutron flux in the niche of experimental devices with different environment

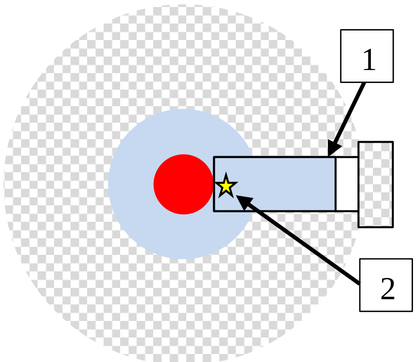
Neutron energy	Neutron flux, cm^{-2}·s^{-1}	
	Air	Water
$0 < E_n < 1$ keV	1.3·10^8	1.1·10^8
1 keV $< E_n <$ 10.5 MeV	4.0·10^7	2.4·10^7

Further, the influence of water screens on the radiation characteristics in the niche of experimental devices for the current configuration was studied (Table 4). The niche is filled with air. Water screens are installed between the core and the irradiated object. The distance to the irradiation position does not change. In the absence of water screens, the neutron flux increases by more than three orders of magnitude, but the neutron spectrum becomes harder (the cadmium ratio decreases from 11.2 to 4.6) and the gamma radiation component increases by more than 5 times. Such conditions, of course, are unacceptable for silicon doping, since doping efficiency will be reduced and the number of defects in the ingot lattice and energy release will increase.

Table 4. Radiation characteristics in the niche of experimental devices with and without a water screen

Characteristic	With water screens	Without water screens
Flux density of neutrons with energy < 1 keV, cm^{-2}s^{-1}	1.3·10^8	2.0·10^{11}
Flux density of neutrons with energy > 1 keV, cm^{-2}s^{-1}	4.0·10^7	8.5·10^{10}
Gamma radiation flux (1 eV – 10.5 MeV), cm^{-2}s^{-1}	1.5·10^{11}	8.0 10^{11}

The particular cases considered have shown that it is possible to improve the radiation characteristics in the niche of experimental devices by creating a water environment in the irradiation position, but it is necessary to take into account one more important factor affecting silicon doping – the neutron intensity. During neutron-transmutation doping of silicon ingots, it is necessary to accumulate a thermal neutron fluence in the irradiated ingot of more than 10^{17} cm^{-2}, so the neutron intensity should be such as to achieve the required neutron fluence in an acceptable time. Therefore, to increase the intensity of neutrons in the irradiation position, it is necessary to bring it closer to the core and create a water environment in it (Figure 3), i.e. niche needs to be upgraded. The results of calculations for the upgraded niche configuration are shown in Table 5. The distance from the central axis of the core to the irradiation position is 573 mm. The niche is filled with water. There are no water screens.



1 – additional tank with water; 2 – irradiation position

Figure 3. Schematic view of the irradiation position

Table 5. Radiation characteristics in the niche of experimental devices with an upgraded configuration

Characteristics	Value
Thermal neutron flux (<0.465 eV), cm^{-2}s^{-1}	9.9·10^{10}
Fast neutron flux (> 0.1 MeV), cm^{-2}s^{-1}	1.4·10^{10}
Neutron flux (< 1 keV), cm^{-2}s^{-1}	1.1·10^{11}
Neutron flux (> 1 keV), cm^{-2}s^{-1}	1.9·10^{10}
Axial non-uniformity of thermal neutron flux (<1 keV), %	25
Thermal to fast neutron ratio	6.9
Fraction of thermal neutrons in the integral flux, %	79
Gamma radiation flux (1 eV – 10.5 MeV), cm^{-2}s^{-1}	9.5·10^{12}
Cadmium ratio	9.6

Such a modernization of the irradiation position in the niche made it possible to create conditions that meet the main criteria, which will have a positive effect on the effective doping of silicon ingots. In particular, the proposed niche configuration will lead to the fulfillment of the following criteria: the ratio of the thermal to fast neutron flux (6.9 with a criterion of 7.0) and the cadmium ratio (9.6 with a criterion of 10). Those indicates the creation of a «soft» (more thermal) neutron spectrum in the irradiation area.

Another important criterion is the formation of a uniform neutron flux profile during irradiation of a silicon ingot both in height and in diameter. One of the methods for reducing the axial non-uniformity of the neutron flux can be the use of shielding materials, which requires the development of a special irradiation device. Before developing the design of the irradiation device, it is necessary to study the radial and vertical profile of the neutron flux in the unperturbed irradiation position, i.e. without silicon ingot. The results of such studies are shown in Figures 4 and 5.

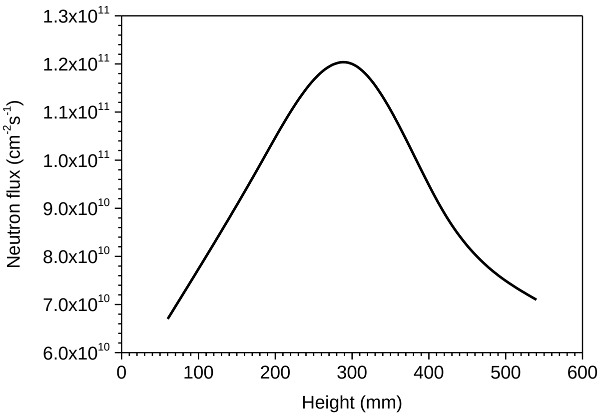
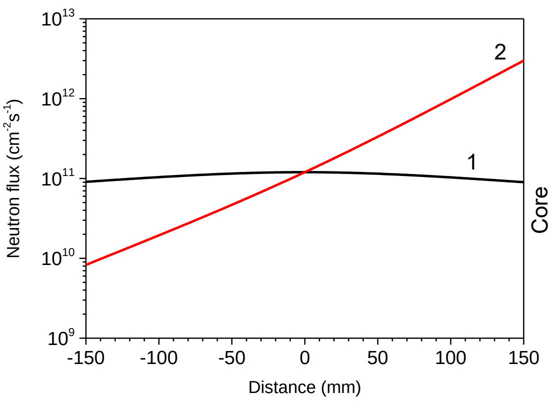


Figure 4. Axial distribution of neutron flux (E_n < 1 keV)



1 – distribution over the ingot diameter;
2 – distribution in the depth of the ingot

Figure 5. Distribution of neutron flux (E_n < 1 keV):

The nonuniformity of the neutron field profile (E_n <1 keV) was 11% in diameter and 25% in height. The design of the irradiation device will have to ensure the inhomogeneity of the neutron field within 8% along the height of the ingot and within 5% along the diameter of the ingot.

Conclusion

The obtained results of the computational studies have shown that the conditions for irradiating silicon ingots with diameter more than 200 mm in the currently existing configuration of the niche of experimental devices do not meet the specified criteria. The modification of the niche configuration proposed in this paper will make it possible to create conditions for efficient doping of silicon ingots of the large diameter. However, the inhomogeneity of the neutron field over the diameter and height of the silicon ingot will remain above the allowable values. From which it follows that it is necessary to develop a special irradiation device that forms a uniform neutron field, which will make it possible to obtain silicon ingots with a high uniformity of the final resistivity, which is also an important criterion when doping silicon.

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ВВР-К РЕАКТОРЫНЫҢ ЭКСПЕРИМЕНТТІК ҚҰРЫЛҒЫЛАРЫНЫҢ ТАУАШАСЫНДАҒЫ РАДИАЦИЯЛЫҚ СИПАТТАМАЛАРДЫ ЕСЕПТІК ЗЕРТТЕУ

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Ядролық реактор – сәулеленуді генерациялайтын күрделі инженерлік-техникалық қондырғы. Сондықтан ядролық реактордың радиациялық сипаттамаларын эксперименттік өлшеу күрделі міндет болып табылады және кейбір жағдайларда техникалық жағынан мүмкін болмай жатады. Есептеу кодтары мен құралдары жақсы дамыған заманда ядролық реактордың радиациялық сипаттамаларын айтарлықтай дәлдікпен және нақтылықпен айқындауға мүмкіндік бар. Осыған байланысты ядролық реакторда болатын физикалық процестерді компьютерлік модельдеу ғылыми зерттеулердің негізгі әдістерінің біріне айналды. ВВР-К реакторы – көп көлемде тік және көлденең сәулелендіру позициялары бар көп мақсатты зерттеу реакторы, ол кең ауқымды ғылыми және қолданбалы міндеттерді шешу үшін пайдаланылады. ВВР-К реакторындағы ең үлкен көлемдегі сәулелендіру позициясы эксперименттік құрылғыларға арналған тауаша болып табылады, бұл диаметрі 1000 мм дейінгі объектілерді сәулелендіруге мүмкіндік береді. Аталған позиция диаметрі 200 мм-ден асатын кремний құймаларын нейтрондық-трансмутациялық легирлеу үшін кандидат ретінде қаралады. Мақалада ВВР-К реакторының эксперименттік құрылғылары тауашасының қолданыстағы және жаңартылған конфигурациясының радиациялық сипаттамалары ұсынылған. Конфигурацияны жақсарту сәулелендіру позициясындағы нейтрондық сипаттамаларды жақсартатыны көрсетілген.

Түйін сөздер: *ВВР-К, эксперименттік құрылғылардың тауашасы, радиациялық сипаттамалар, кремнийді нейтрондармен трансмутациялық легирлеу (NTD-Si), Монте-Карло (MCNP) әдісімен иондаушы сәулеленуді тасымалдауды модельдеу.*

РАСЧЕТНОЕ ИССЛЕДОВАНИЕ РАДИАЦИОННЫХ ХАРАКТЕРИСТИК В НИШЕ ЭКСПЕРИМЕНТАЛЬНЫХ УСТРОЙСТВ РЕАКТОРА ВВР-К

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Ядерный реактор – сложная инженерно-техническая установка, генерирующая излучение. Поэтому экспериментальные измерения радиационных характеристик ядерного реактора является сложной задачей, и в некоторых случаях технически невозможной. Современное развитие расчетных кодов и инструментов позволяет определить радиационные характеристики ядерного реактора с достаточной точностью и достоверностью. В связи с этим, компьютерное моделирование физических процессов, происходящих в ядерной реакторе, стало одним из основных методов научных исследований. Реактор ВВР-К это многоцелевой исследовательский реактор с большим количеством вертикальных и горизонтальных облучательных позиций, используемых для решения широкого круга научных и прикладных задач. Облучательная позиция с наибольшими размерами в реакторе ВВР-К представляет собой нишу для экспериментальных устройств, что позволяет проводить облучение объектов диаметром до 1000 мм. Данная позиция рассматривается в качестве кандидата для нейтронно-трансмутационного легирования слитков кремния диаметром более 200 мм. В статье представлены радиационные характеристики текущей и модернизированной конфигурации ниши экспериментальных устройств реактора ВВР-К. Показано, что усовершенствование конфигурации приводит к улучшение нейтронных характеристик в облучательной позиции.

Ключевые слова: *ВВР-К, ниша экспериментальных устройств, радиационные характеристики, трансмутационное легирование кремния нейтронами (NTD-Si), моделирование переноса ионизирующего излучения методом Монте-Карло (MCNP).*