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Technical Note

Shielding design and analyses of the cold neutron guide hall for the KIPT neutron source facility

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ABSTRACT

Argonne National Laboratory of the United States and Kharkov Institute of Physics and Technology (KIPT) of Ukraine have cooperated on the development, design, and construction of a neutron source facility. The facility was constructed at Kharkov, Ukraine, and its commissioning process is underway. The facility will be used for researches, producing medical isotopes, and training young nuclear specialists. The neutron source facility is designed with a provision to include a cryogenically cooled moderator system—a cold neutron source (CNS). This CNS provides low-energy neutrons, which will be used in the scattering experiment and material structures analysis. Cold neutron guides, coated with reflective material for the low-energy neutrons, will be used to transport the cold neutrons to the experimental site. The cold neutron guides would keep the cold neutrons within certain energy and angular space concentrated inside, while most of the gamma rays and high-energy neutrons are not affected by the cold neutron guides. For the KIPT design, the cold neutron guides need to extend several meters outside the main shield of the facility, and curved guides will also be used to remove the gamma and high-energy neutron. The neutron guides should be installed inside a shield structure to ensure an acceptable biological dose in the facility hall. Heavy concrete is the selected shielding material because of its acceptable performance and cost. Shield design analysis was carried out for the CNS guide hall. MCNPX was used as the major computation tool for the design analysis, with neutron and gamma dose calculated separately. Weight windows variance reduction technique was also used in the shield design. The goal of the shield design is to keep the total radiation dose below the 5.0 μSv/hr guideline outside the shield boundary. After a series of iterative MCNPX calculations, the shield configuration and parameters of CNS guide hall were determined and presented in this article.

1. Introduction

In the recent years, cold neutrons, with characteristic wavelength larger than 4.0 Å (energy less than ~ 5.0 meV), have been increasingly important for the studies in the condensed matter physics. Cold neutrons could be used for diffraction and small-angle scattering experiments resolving mesoscopic structures. A cold neutron research facility would be a powerful national resource for promoting the national capacity for science and technology. However, in most of the reactors in the world, the fraction of low-energy neutrons ($E < 10$ meV) is very small because of the upscattering of thermal moderator, and a cryogenically cooled moderator system, which is called cold neutron source (CNS), would be needed to generate high-intensity cold neutron beams.

Argonne National Laboratory and National Science Center—Kharkov Institute of Physics and Technology have been collaborating on developing and constructing a neutron source facility at KIPT that uses an electron accelerator–driven subcritical assembly [1]. Tungsten or natural uranium is used as the target material. The neutron source facility will be driven by 100 kW electron beam with electron energy 100 MeV. The facility has been constructed, and it is being commissioned. The main functions of this facility are medical isotope production and support of the Ukraine nuclear industry. This neutron source facility is designed with a provision to include a cryogenically cooled moderator system—a CNS, using liquid hydrogen as cold moderator. A large CNS beam tube is reserved in the water tank to install the CNS and related instruments. Outgoing neutrons are coupled with cold neutron guides [2] and coated with reflective material for low-energy neutrons to transport the cold neutron beams to the experiment sites. The coating material (mirror or supermirror) is only reflective

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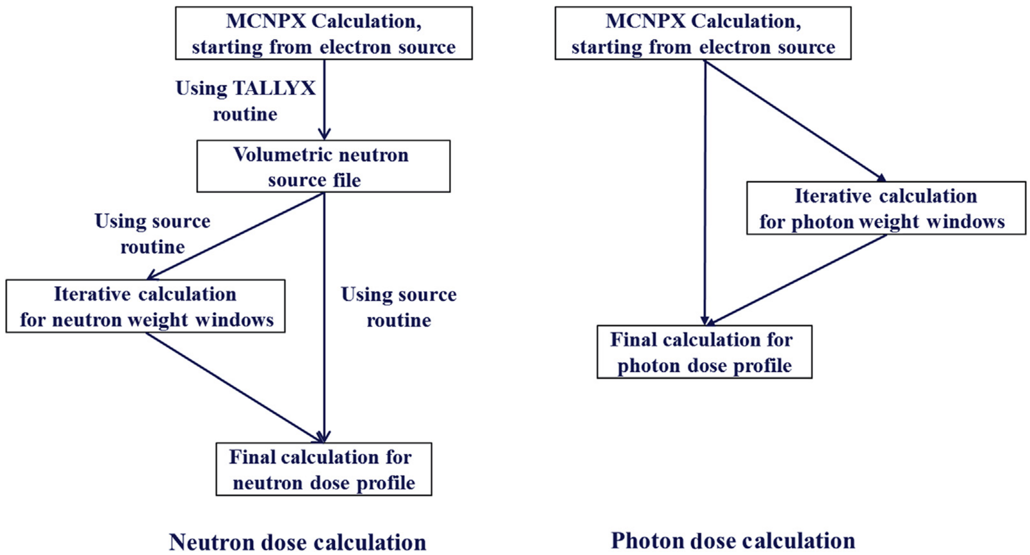


Fig. 1. MCNPX calculation process for neutron and photon dose.

to cold neutrons within certain energy and angular space, while it has very little impact on gamma and high-energy neutrons.

The gamma and high-energy neutrons would be noise for the cold neutron experiments. To reduce the level of gamma and high-energy neutron flux at the exit of the cold neutron guides, the neutron guide needs to be long enough (up to 100 m) if only straight guide is used, or a curved guide with certain bending angle should be adopted. For the KIPT neutron source facility, owing to the space limit and cost, curved neutron guides would be used to lower the gamma and high-energy neutron flux. The total length of neutron guides would be 5.0–6.0 m. About 1.2 m of guide is located inside the main shield of the facility, whereas the rest parts of guide line would extend outside, and an additional shielding structure is required. Walls composed of movable heavy concrete blocks are planned to be installed surrounding the cold neutron guides outside the main reactor shield, constructing the CNS guide hall to install experimental hardware.

Shielding design and analysis are performed for the CNS guide hall. This shielding study defined the radiation dose outside the shield boundary of the CNS guide hall as a function of the shield thickness and other parameters. The main objective is to reduce the biological dose to permit personnel to work outside the CNS guide hall during operation. The shield design was configured to reduce the biological dose to less than 5.0 μSv/hr; this value is a factor of 5 less than the international standard of 25.0 μSv/hr for occupational limit, assuming 40-h work per week and 50 weeks per year.

The shielding analyses require accurate characterization of the neutron and photon fluxes through the shield. The Monte Carlo computer code MCNPX [3] was used with ENDF/B-VII [4] nuclear data libraries for performing the shielding analyses due to its updated capability for electron-, photon-, and neutron-coupled transport calculation. Given the fact that the neutron and gamma flux outside the shield boundary is very low to meet the working dose requirement, a direct analog MCNPX calculation is very time-consuming and actually not practical. Variance reduction techniques must be introduced to deal with the shielding problem with deep penetration. Three-dimensional mesh-based weight windows were used [5,6], which could provide a space- and energy-dependent importance function for the calculation model; therefore, much more particles can be tracked outside the shield. The weight windows are generated to optimize a special tally. Considering the complicated geometry of the CNS guide hall, multiple sets of weight windows, which are optimized for tallies at different locations of external shield boundary, are needed for an accurate neutron or gamma dose profile along the whole external boundary of the CNS guide hall.

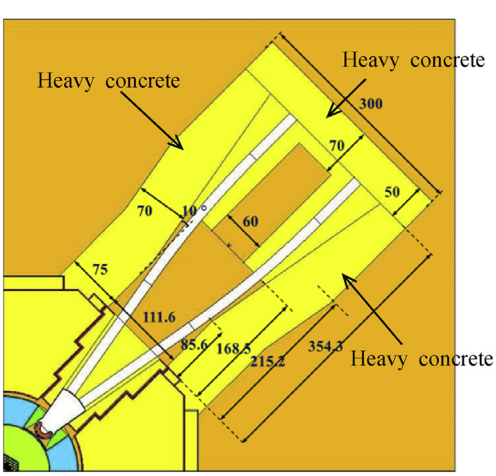


Fig. 2. Radial configuration of the CNS guide hall at the core midplane, with dimensions (unit: cm).
CNS, cold neutron source.

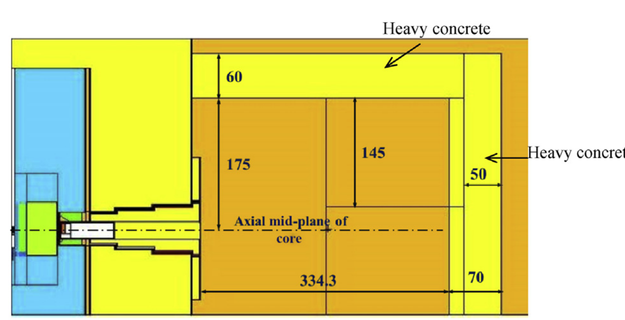
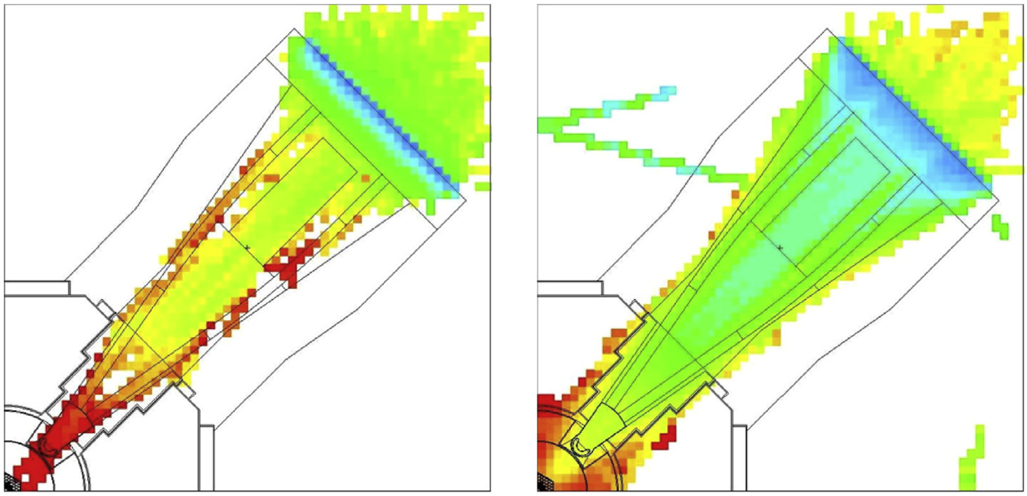
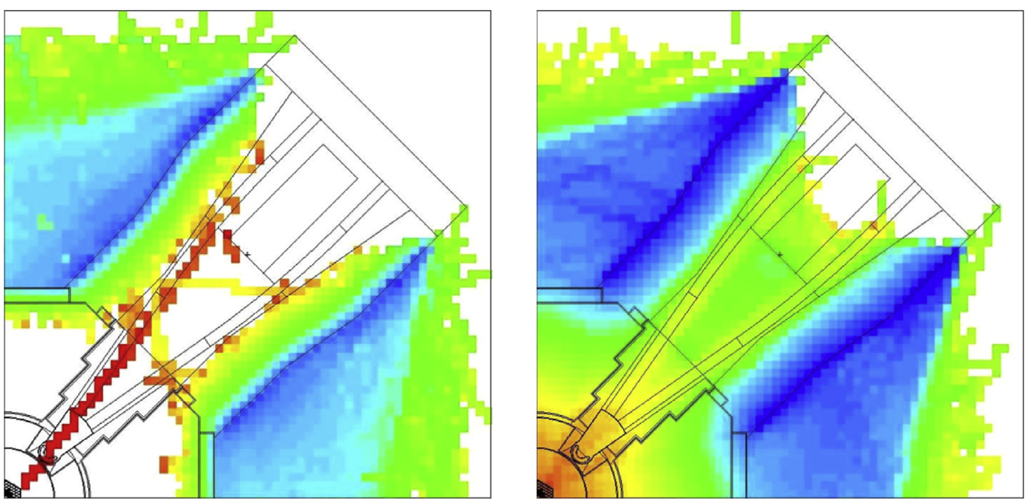


Fig. 3. Axial configuration of the CNS guide hall across the shield symmetric plane, with dimensions (unit: cm).
CNS, cold neutron source.



$E < 1.0$ MeV $E > 1.0$ MeV

Fig. 4. Weight windows optimized for photon dose outside the end wall in radial view across the core midplane.



$E < 1.0$ MeV $E > 1.0$ MeV

Fig. 5. Weight windows optimized for photon dose outside the sidewall in radial view across the core midplane.

Table 1
Composition of ferrophosphorus heavy concrete.

Element	Weight fraction	Atom fraction	Atom density (atom/b*cm)
H	0.005000	0.158643	0.014339
O	0.104000	0.207881	0.018790
Mg	0.002000	0.002632	0.000238
Al	0.004000	0.004741	0.000429
Si	0.034000	0.038715	0.003499
P	0.197000	0.203403	0.018385
Ca	0.042000	0.033514	0.003029
Fe	0.612000	0.350472	0.031678

2. Calculation model and method

For this shield analysis, to improve the efficiency of Monte Carlo calculation, a quarter neutron source facility model was introduced with reflective boundary conditions on the symmetric line, using the symmetry of the subcritical assembly in the KIPT neutron source facility. Natural uranium target was used because of its larger neutron yield and neutron and photon flux level than the tungsten target. The CNS and other experimental instruments, which are installed outside the graphite reflector, do not follow the quarter symmetry. However, these instruments are far from the reactor core and have very little impact on the subcriticality and neutron flux level.

For the electron accelerator–driven neutron source facility, the neutron yield from the electron is very small. For the KIPT facility using uranium target, with the electron energy 100 MeV, the neutron yield per electron is only ~0.05. In addition, owing to the fact that the electron transport is time-consuming, it is expensive to accurately tally the neutron dose outside the shield boundary with the calculation starting from electron particles. Another procedure was used, with neutron and photon dose calculated separately. First, a volumetric neutron source file was generated by a separate MCNPX calculation starting from electron source particles [7]. This neutron source file recorded the position, energy, weight, and cosine directions of every born neutron inside the target. The TALLYX [3] user subroutine of MCNPX was modified

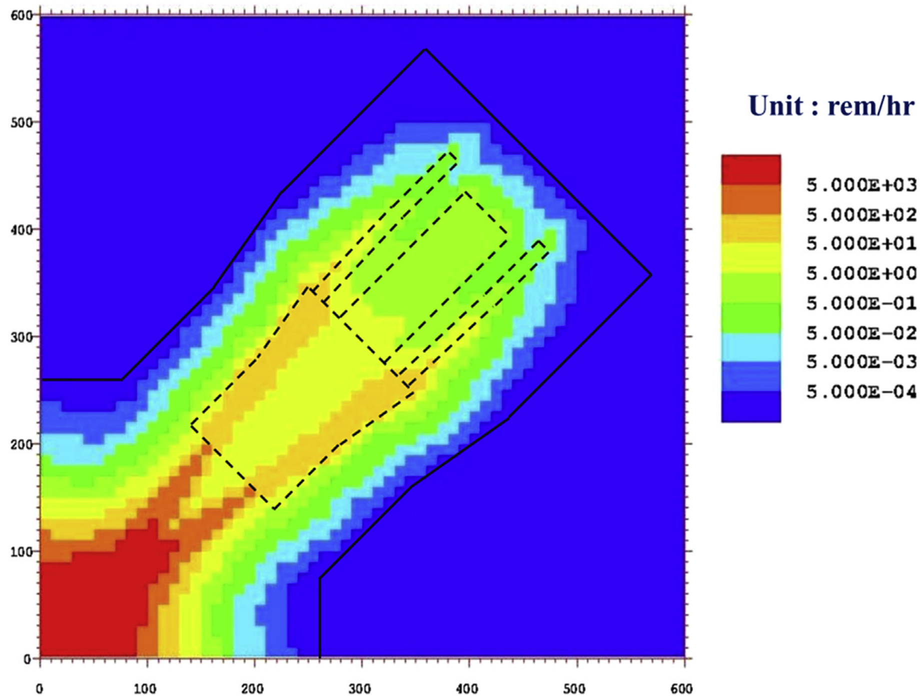


Fig. 6. Neutron biological dose profile of the CNS guide hall in radial view across the core midplane. CNS, cold neutron source.

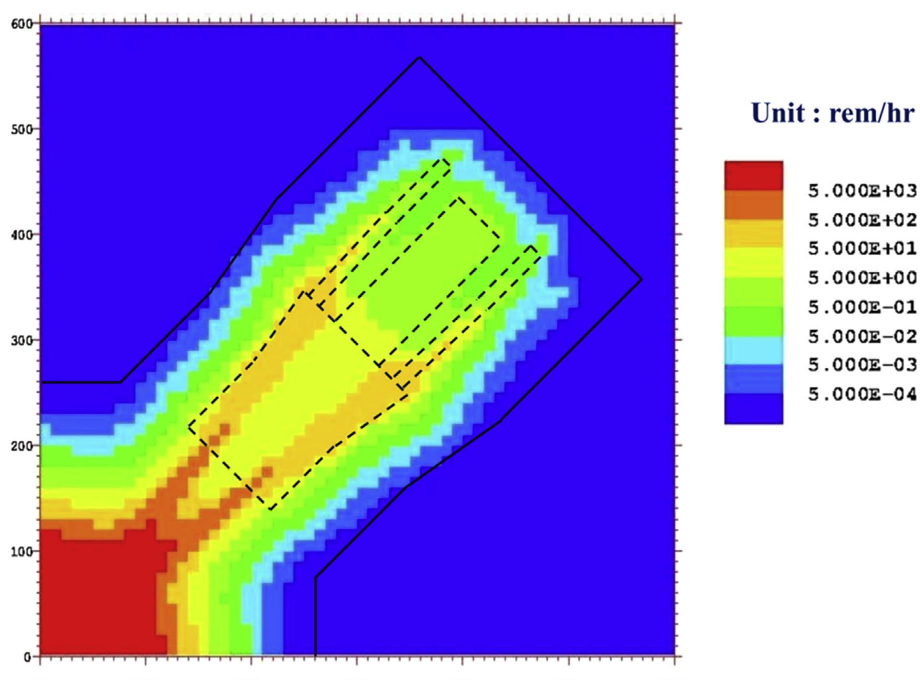


Fig. 7. Photon biological dose profile of the CNS guide hall in radial view across the core midplane. CNS, cold neutron source.

and used to generate the volumetric neutron source file, and the neutron yield from electron particles could be preserved. The SOURCE [3] user subroutine was modified and used to read the external neutron source file to start a new calculation for the neutron dose, and only neutron transport was involved in this calculation. In this neutron transport calculation, each record on the neutron source file could be tracked multiple times to reduce the statistical error. For the photon dose, it was obtained through an electron-, photon-, and neutron-coupled transport calculation, which starts from the electron source particles. In this way, the contribution of photons caused by both neutron fissions in the fuel region and by electrons in the target could be included. The weight windows variance reduction technique of MCNPX was also used in this study. Mesh-based weight windows [5,6] were

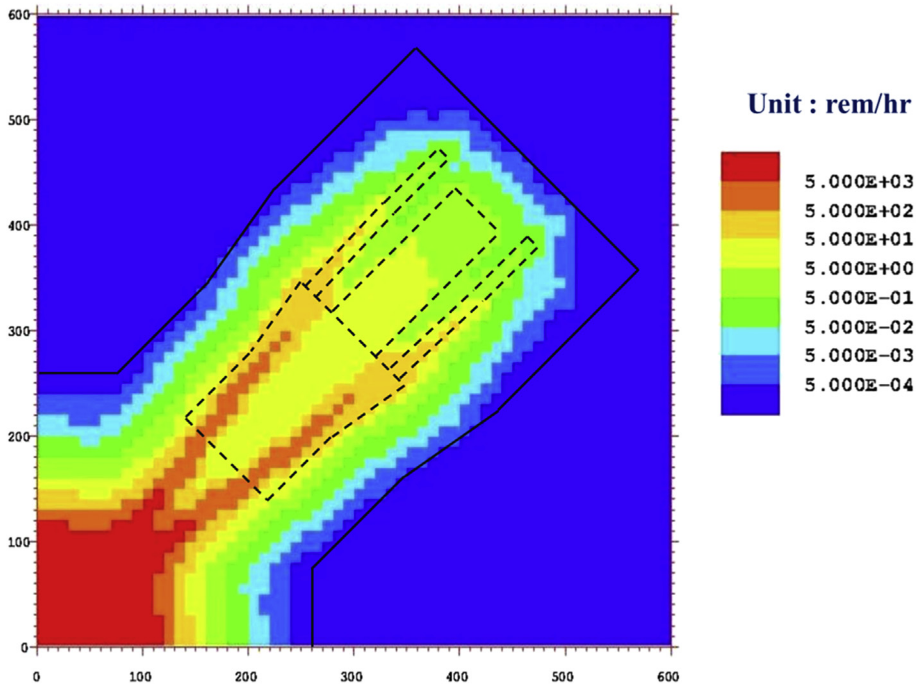


Fig. 8. Total (neutron + photon) biological dose profile of the CNS guide hall in radial view across the core midplane. CNS, cold neutron source.

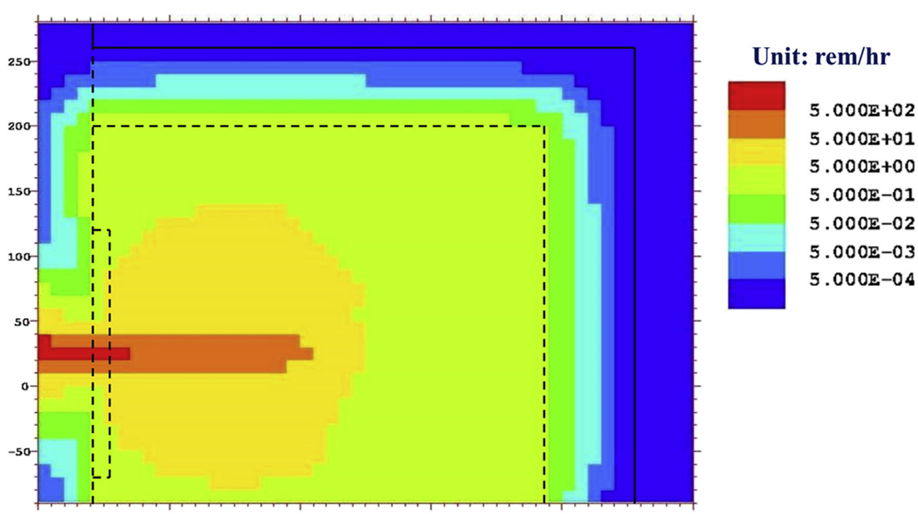


Fig. 9. Neutron biological dose profile across the shield symmetric plane of the CNS guide hall in axial view. CNS, cold neutron source.

generated using iterative MCNPX calculations for both neutrons and photons. The calculation process of MCNPX for neutron and photon dose profiles is summarized in Fig. 1 [8]. Modified TALLYX and SOURCE user subroutines are needed in the neutron dose calculation, whereas standard MCNPX could calculate the photon dose.

The calculation model of MCNPX is shown in Figs. 2 and 3 in radial and axial view, respectively. For the configurations shown in Fig. 2, reflective boundaries were used on the left and bottom surfaces which are the symmetric lines of the subcritical assembly. The shield geometry and parameters were determined after a series of MCNPX calculation, which would be explained in the following sections of this article. Sufficient empty space has been reserved inside the CNS guide hall for the experimental instruments. In this model, no shield credit is taken for the experimental hardware for the CNS because it will change depending on the experiment, and this approach would also give a conservative shield design. In the design shown in Figs. 2 and 3, it is assumed that the curved neutron guide would have a bending angle of 10°. If the bending angle changes, the shield geometry might need change slightly. Shielding material needs to be installed surrounding the curved guides adjacent to the center of the curved guide to lower the gamma and

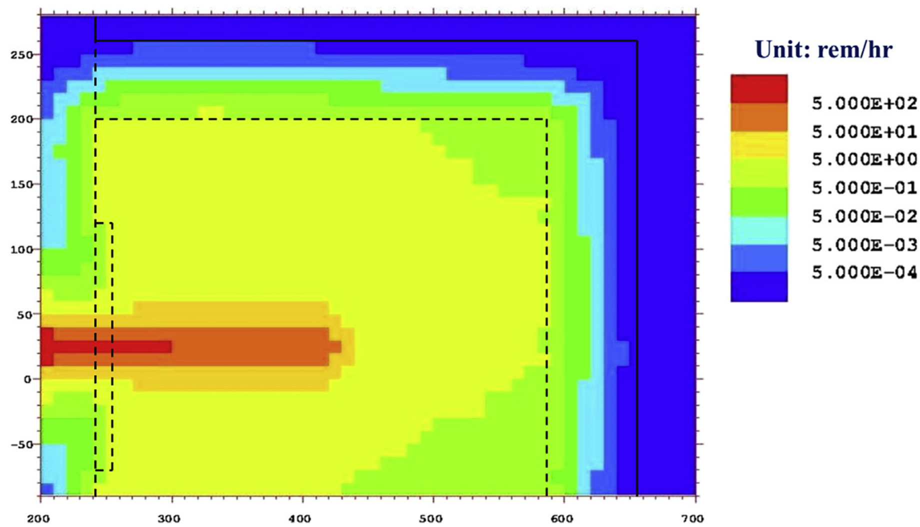


Fig. 10. Photon biological dose profile across the shield symmetric plane of the CNS guide hall in axial view. CNS, cold neutron source.

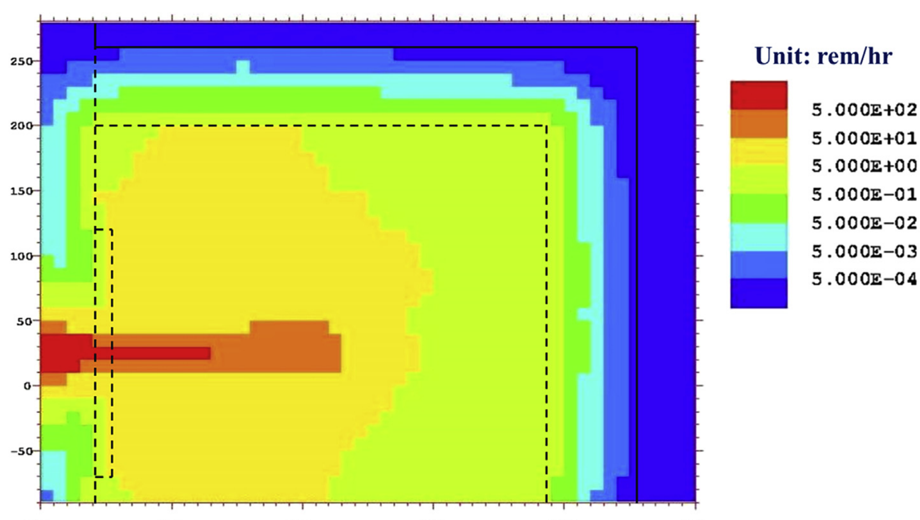


Fig. 11. Total biological dose profile across the shield symmetric plane of the CNS guide hall in axial view. CNS, cold neutron source.

high-energy neutron flux at the guide exit. The thickness of cold neutron guides, normally made of aluminum alloy, is less than 1 cm. Therefore, the cold neutron guides themselves make very little contribution to the shield design and are not modeled in the MCNPX calculation.

The weight windows for neutron and photon dose calculation are also generated separately. The weight windows are generated to optimize a special tally as described previously; therefore, the shield design and iterative MCNPX calculation of the end wall and sidewall were performed separately using corresponding weight windows. One example of weight windows for photon dose calculation, with the finalized shield geometry and parameters, are shown in Figs. 4 and 5. These two photon weight windows were optimized for the tallies on the external surface of end wall and sidewalls. In both of these two weight windows, the weight of photon is high at the reactor core region (the weight values are ~ 1.0 or higher) and decreases along the direction toward the external shield boundary where the interested tally is located (the weight values are in the range of 1.0e-08–1.0e-07), and photon particles would split based on the value of weight to reduce the statistical error.

3. Shielding results

In this shield design analysis, ferrophosphorus heavy concrete with density 4.8 g/cm^3 is used to compose the CNS guide hall. This type of heavy concrete is selected because of its high density and balanced mixture of light and heavy nuclei, as well as the easy availability. The composition of the ferrophosphorus heavy concrete is shown in Table 1 [9].

For the shield design, an iterative process is used to search the shield geometry and parameters, which is described as follows: At first, an initial guess of the shield geometry and parameters was given, and weight windows were generated and used to calculate the neutron and photon biological dose outside the shield. The neutron and photon biological doses were obtained by using International Commission on Radiological Protection-21 (1971) [10] flux-to-dose conversion tables of MCNPX. Based on these dose results, the shield geometry and parameters were revised, and the biological dose was recalculated. Many of these iterations might be needed to get the finalized shield geometry and parameters, for which the 5.0 μSv/hr contour line of the total dose (neutron + photon) is kept inside but close to the external shield boundary.

Using the method described previously, after a series of iterative MCNPX calculation, the geometry and parameters of the CNS guide hall shield design were finalized, as shown in Figs. 2 and 3 in radial and axial views, respectively. For the radial configuration of the CNS guide hall, the heavy concrete shield thickness of the end wall is from 50–70 cm, whereas the shield thickness of the sidewall is in the range of 70–75 cm. The experimental sites are not modeled in this analysis because they will vary depending on the experiment. However, it is determined that 50 cm of heavy concrete after the outlet of neutron guides is sufficient to lower the total biological dose < 5.0 μSv/hr. For the axial configuration, the heavy concrete shield thickness of the top ceiling is 60 cm.

The neutron and photon dose profiles across the CNS guide hall, with finalized geometry, were calculated using the mesh tally capability of MCNPX, as shown in Figs. 6–8 in radial view and in Figs. 9–11 in axial view, assuming the neutron source facility was operated under full electron beam power (100 kW). In these figures, the solid lines represent the external boundary of heavy concrete shield, whereas the dashed lines represent the internal boundary of CNS guide hall. Figs. 6, 7, 9, and 10 are not the direct results from MCNPX calculation, but each was obtained by merging two separate set of MCNPX results using different weight windows. For example, for the gamma dose profile shown in Fig. 7, two dose results were calculated separately using the weight windows shown in Figs. 4 and 5, and these two results were merged together by selecting the dose value with the smaller statistical error. In this way, the gamma biological dose map could have relatively small statistical errors along the whole shield boundary (both end wall and sidewall). The same procedure was used to get the neutron and photon dose maps shown in Figs. 6, 9, and 10. The total biological dose map in radial view, across the core midplane where the peak radiation dose appears, is shown in Fig. 8, and it is obtained by adding the two maps shown in Figs. 6 and 7. The total biological dose map in axial view, across the shield symmetric plane, is shown in Fig. 11, and it is obtained by adding the two maps shown in Figs. 9 and 10.

Based on the results shown in Figs. 8 and 11, the 5.0 μSv/hr contour line is kept inside and close to the external shield boundary, which satisfies the design requirements. For both figures, the 5.0 μSv/hr contour line is away from the external shield boundary at the corners, which means round corners could be adopted in the real construction of CNS guide hall. The maximum statistical error for the biological dose results, along the shield boundary, is less than 10%. It can also be seen that in both radial and axial configurations, close to the external shield boundary, the neutron dose and gamma dose are about in the same order of magnitude. This phenomena is different from those in the main facility shield design [6], in which neutron dose dominates the shield design because of the very high-energy neutrons ($E > 10$ MeV) generated inside the target, whereas the contribution from gamma and fission neutrons is much smaller at the external shield boundary. The reason is that for this CNS guide hall shield design, there exists large empty space inside the shield for neutron guides and other equipment, and the gamma and fission neutrons could also leak out though neutron guides and make larger contribution to the dose at external shield boundary, compared with the very high-energy neutrons generated inside the target.

4. Summary and conclusion

For the KIPT neutron source facility, cold neutron guides are needed to be coupled with the CNS and transport the cold neutrons to the experimental sites. The neutron guides should be installed inside a shield structure, guide hall, to ensure an acceptable biological dose outside the shield. The shielding design and analysis of the CNS guide hall of the KIPT neutron source facility were carried out successfully. Heavy concrete was selected as the shielding material because of its acceptable performance and cost. The Monte Carlo computer code MCNPX was used for performing the analysis. A quarter neutron source facility model, with reflective boundary conditions on the symmetric lines of the subcritical assembly, was introduced to improve the calculation efficiency. The neutron and photon doses were analyzed using separate MCNPX calculations to reduce the statistical error in the results and to use reasonable computer resources. A neutron source file was developed and used to calculate the neutron dose map, whereas the photon dose map was obtained from MCNPX calculation starting directly with the electron source. The weight windows variance reduction technique was used for both the neutron and photon dose calculations; this was essential in these analyses to reduce statistical errors. After a series of iterative MCNPX calculations, the shield geometry and parameters of the CNS guide hall shield were determined, and the total biological dose outside the shield boundary is less than the 5.0 μSv/hr design guideline.

Conflict of interest

There is no conflict of interest.

Acknowledgments

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