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Calculation of neutron/gamma dose rates' distributions inside TRR neutron diffraction facility laboratory using computational method

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HIGHLIGHTS

- Neutron diffraction laboratories are one of the most important applications of research reactors.
- Computational methods help to estimate neutron/gamma dose rates before high cost designs.
- Neutron/Gamma dose rate should be mapped to provide awareness for neutron laboratory users.
- Measurements help to benchmark the carried out simulations.

ABSTRACT

Neutron scattering facilities are widely applied to study the properties of materials. A beam of monochomatic neutrons or a widespread wavelength band of neutrons is used to irradiate the sample which is going to be analyzed at the scattering laboratory. Shielding of incident neutrons also the scattered ones from the sample should be definitely done to decrease the laboratory dose rates. Also, mapping of the dose rate distributions helps to the laboratory users to avoid high neutron/gamma exposures. The present study uses a computational method to simulate neutron and gamma dose rates distributions inside TRR diffraction facility laboratory. Not only the simulation method helps to design the laboratory boundary or the laboratory walls so that behind its walls the personal exposures remain as low as possible, but also gives warnings to the facility users about the high dose regions around the beam exit when the facility is under operation. The carried-out work showed after the laboratory boundary, summation of the neutron and gamma dose rates are less than 3 μSv.h^{-1}. In addition, the carried-out benchmark studies by using experimental data in this work confirms the simulations with less than 20% relative discrepancy.

KEYWORDS

Neutron dose rate
Gamma dose rate
Diffraction laboratory
MCNPX code

HISTORY

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1 Introduction

Various neutron laboratories have been equipped and used around research nuclear reactors. These laboratories are designed in such a way that the neutron guides and neutron filters can select the required neutron wavelength for theoretical investigates and at the same time avoid the presence of other neutron wavelengths, especially fast neutrons, in the analysis place of the equipped laboratory. These neutron filters help the analysis to be performed more accurate without a noticeable neutron background, while reducing the exposure of the laboratory staff.

Some materials have been proposed as the most effective neutron filters. Among these crystalline neutron filters some of them have found more attraction to be used in nuclear industry for example quartz (SiO_2), bismuth, silicon, germanium, lead and sapphire (Al_2O_3) (Adib, 2008). Among the mentioned crystals, single crystal of Al_2O_3 called sapphire has been showed an operative fast neutron filter and has been used in many neutron facilities (Stamatelatos and Messoloras, 2000).

Sapphire is an effective fast-neutron filter meanwhile its transmission for $\lambda_n < 0.04$ nm (500 meV) is less than 3% in the case of a 100 mm-thick crystal. It is also an operative filter of thermal neutrons with $\lambda_n < 0.1$ nm, while there is an excessive density of high-order reflections available to scatter the incident beam. Additional gain of the crystal than the other neutron filters is that cooling of the crystalline filter has only a negligible effect on its neutron transmission for its high Debye temperature ($\theta_D = 1040$ K) (Mildner et al., 1993). Advanced System for Tomography and Radiography (ASTOR) of the multipurpose reactor RA-10 uses neutron guides to transfer

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thermal neutrons up to the sample table positioned 17 meters far from the reactor core center. The facility uses 75 cm-thick heavy concrete walls to decrease the neutron and gamma dose rates to less than 3 μSv.h^{-1} and 0.5 μSv.h^{-1} in the case of opened and closed beam shutter situations respectively; the laboratory room dose rate mapping in open-shutter situation is shown in Fig. 1 (Vega et al., 2023).

Zhong and Gohar (Zhong and Gohar, 2018) reported that Argonne National Laboratory (AN) located in United States and Kharkov Institute of Physics and Technology (KIPT) located in Ukraine have collaborated on the development, design, and construction of a neutron source facility. The neutron source facility is considered with a launch to include a cold neutron source (CNS). For this facility, heavy concrete is the selected as shielding material because of its acceptable performance and cost. The shield design was configured to reduce the biological dose to less than 5 μSv.h^{-1}, which the value is 5 times less than the international standard of 25 μSv.h^{-1} for occupational limit. The value was extracted with the assumption of 40 hours work per week and 50 weeks per year. They by using the MCNPX simulation code showed that for the radial configuration of the cold neutron source guide hall, the heavy concrete shield thickness of the end wall could be from 50 cm - 70 cm, while the thickness of the side wall is in the range of 70 cm to 75 cm. The authors mentioned that they did not model the experimental sites in their analysis, because the sites are various depending on the experiment. Also, they mentioned that 50 cm of heavy concrete after the outlet of neutron guides is satisfactory to subordinate the total biological dose rates to < 5 μSv.h^{-1} (Zhong and Gohar, 2018).

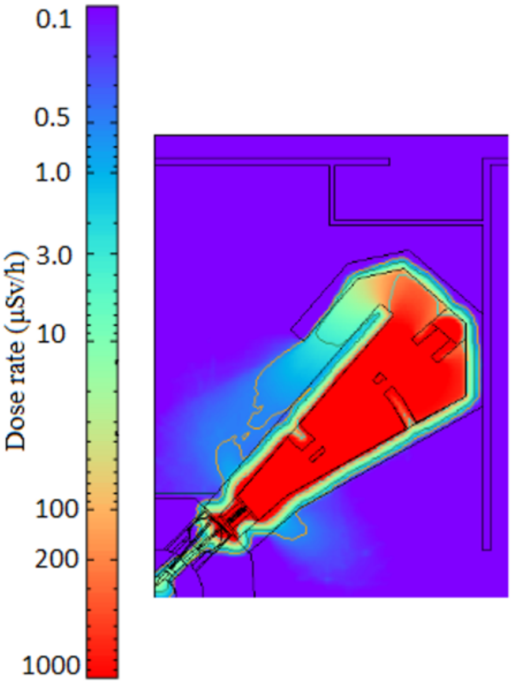

Figure 1: ASTOR neutron dose rate mapping when the facility beam shutter is open (Vega et al., 2023).

Harada et al. (Harada et al., 2011) designed a shield for neutron beam line of NOBORU at JSNS/J-PARC. The instrument which is one of the 23 services in the Materials and Life science experimental Facility (MLF) of Japan Proton Accelerator Research Complex (J-PARC), has been planned to assess characteristics of Japan Spallation Neutron Source (JSNS) and correspondingly the facility is going to be used for a variety of applications. In this project, the dose limit was considered 12.5 μSv.h^{-1} that it could be said the value is as enough as far from the determined value by regulatory limit (25 μSv.h^{-1}). For such areas, the experimenters can stay without time restriction. Borax resin with different thicknesses was used as walls of the experimental room so that keeps the above-mentioned dose rate limit out of the room (Harada et al., 2011).

Also, Sarkawi et al. (Sarkawi et al., 2022) upgraded shielding of Neutron Radiography Imaging (NURI) of 1 MW PUSPATI TRIGA MARK II (RTP) nuclear research reactor. The reactor has located in Malaysian Nuclear Agency. The upgrading has been done because of reducing the staff radiation exposures. Design of the room shielding comprises of some modular blocks built from ordinary concrete and Ferro boron concrete. Ferro boron concrete is used to increase the shielding performance of the facility. With this upgrading, the average radiation dose rate around the facility during the reactor operation at 1 MW reactor power was from 1 μSv.h^{-1} 10 μSv.h^{-1} at different positions (Sarkawi et al., 2022).

HANARO user facilities have been divided into four categories of radiation areas depending on the biological shielding for people who are working inside the radiation-controlled area. The radiation levels of those areas are respectively limited to equal to or less than 6.25, 12.5, and 500 μSv.h^{-1}. The area with a dose rate of about 500 μSv.h^{-1} is restricted to any person when the reactor is operating, this area should be inaccessible by the shielding structure. Heavy concrete is used as material of the shielding room in reactor hall and the wall thickness has been selected 80 cm. Outside this room the radiation level is less than 12.5 μSv.h^{-1} (Wu et al., 2009).

2 Materials and Methods

The present work aims to design a laboratory boundary to shield the neutron and gamma particles emerged from the neutron diffraction facility of Tehran Research Reactor (TRR) when the facility beam shutter is open. MCNPX (Pelowitz, 2008) code was used to modeled the main shield of the facility as well as the laboratory environment. The main shield has been constructed using paraffin, acid boric and lead layers (Menarebazari et al., 2022; Gholamzadeh and Bavarnegin, 2022). The 3D model of the laboratory was presented in Fig. 2-a. The TRR diffraction laboratory was shown in Fig. 2-b. The laboratory room walls are made of common MDF (Medium Density Fiberboard) sheets to make a limited boundary for the laboratory space. The facility main shield which is also seen in Fig. 2-a (covered by MDF housing seen in Fig. 2-b) has been made of different parts that its details reported

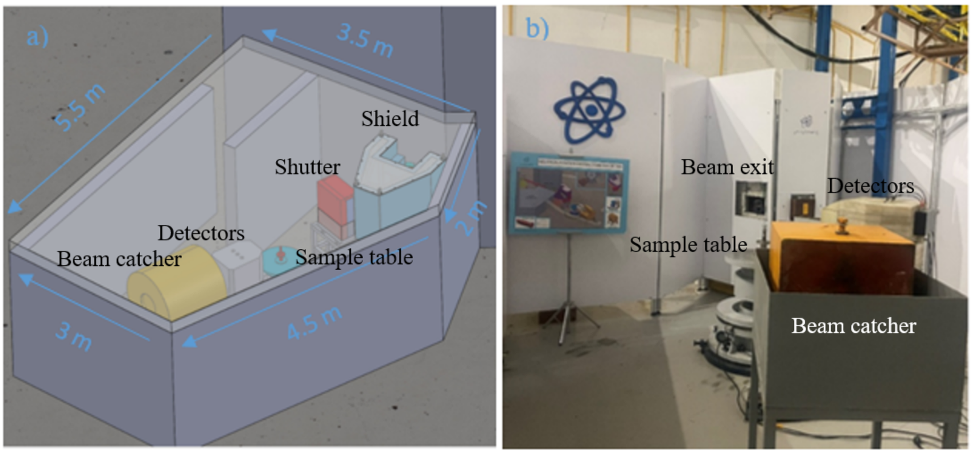

Figure 2: TRR diffraction facility a) Schematic 3D view b) inside the laboratory boundary.

in (Gholamzadeh and Bavarnegin, 2022).

Monochromatic neutron beam of the facility has a flux in order of 10^4 n.s.cm^{-2}. Monochomatic neutron beam rides on the outgoing neutrons (backgrounds) from the second collimator of the diffractometer system. A 7.5 cm sapphire crystal has been used at the beginning of TRR D channel to decrease the fast neutron section of the emerged nuclear core spectrum. The filtered spectrum passes through the first soller collimated ($2 \times 7 \times 120$ cm^3) installed inside the D channel. The collimated neutron beam collides on the PG(002) monochomator surface and a certain wavelength of the incident spectrum reflects according to the Bragg law. The reflected monochomatic beam passes through the second soller collimator ($2 \times 6 \times 80$ cm^3) of the facility. The second collimator is observed in Fig. 3. The reflected neutron spectrum has been used as a source at the second collimator position using MCNPX code to calculate the neutron, as well as secondary gamma dose rates distributions when the TRR is under operation at 5 MW power and the laboratory is active. In addition, the exited gamma from the second collimator has been calculated to be used as a gamma source at this position to calculate the gamma dose rate distribution inside the laboratory room at the same TRR operation condition. Mesh tally card of the computational code was used to calculate the dose rates. In the case of pointwise dose rates, F4-DE/DF tally was used to calculate the dose rate at a point.

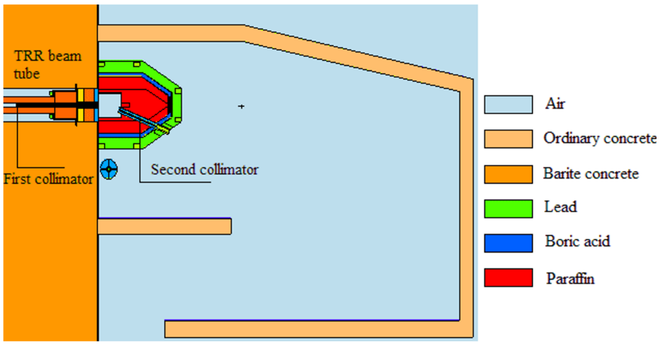

Figure 3: Simulation of TRR diffraction facility and its laboratory room using MCNPX.

It should be noted that the neutron spectrum emerged from the beginning of the D channel enters inside the sapphire crystal which its calculations need an optic-based code such as McStas (`https://www.mcstas.org/`). Then the filtered neutron by the sapphire crystal passes from the first collimator and collides on a PG crystal and then reflects from its surface. So, the neutron spectrum available at the beginning of the channel is calculated using KCODE mode of MCNPX code when whole of the core is simulated. Then the calculated spectrum is used as an input in McStas code to calculate the reflected neutron spectrum when the channel and its optical devices are modeled. The reflected monochromatic spectrum is used as a source in another MCNPX input which models only the facility shields and the laboratory environment to calculate the neutron dose rates. The source position was defined at the second collimator entrance surface. In the case of primary gamma dose rates (the core-emerged ones), the gamma spectrum at the channel exit is calculated using MCNPX code. Then the spectrum is used as a gamma source for the last mentioned MCNPX input to calculate the primary gamma dose rates inside the laboratory. Secondary gammas resulting from (n, γ) reactions on the shield material and the laboratory materials is calculated using the last mentioned MCNPX input. Figure 4 shows the details of the TRR D channel.

A 7%-borated polyethylene sheet ($5 \times 6 \times 20$ cm^3) was considered as the beam shutter which is installed inside the second collimator path when the neutron beam is not going to be used. In this situation also the dose rate distributions were calculated using MCNPX code. All the calculations were done in assumption of the reactor operation at 5 MW power.

3 Results and Discussion

Calculation of neutron spectrum exited from the TRR diffraction facility second collimator showed the neutron background is weak in comparison with the monochomatic beam (Fig. 5). The gamma spectrum exited from this collimator has been presented in Fig. 6. Both spectra were used to calculate the dose rate distribution inside the labo-

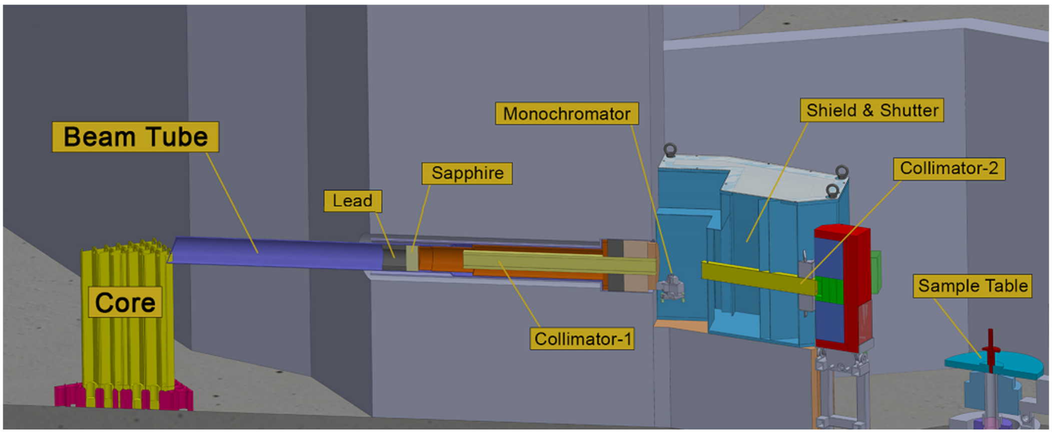

Figure 4: 3D model of TRR diffraction facility obtained using AutoCAD software.

ratory room when the reactor is under full power operation and the beam is under use.

The average neutron dose rate distribution has been calculated using mesh tally card of MCNPX and has been presented in Fig. 7. The figure shows except the beam direction, the other areas inside the laboratory would have a neutron dose rate less than 5 μSv.h^{-1}.

The dose rate distribution has been presented near to the shield and the second collimator installed inside it according to Fig. 8. As the figure shows, far from the direct monochomatic beam the neutron dose rates are less than 4 μSv.h^{-1} which is in conformity with the measured value presented on the figure.

Simulations showed the neutron dose rate at the marked position of the above figure is 2.33 ± 0.02 μSv.h^{-1} which shows very good conformity between the simulation and the measured value (2 ± 0.04 μSv.h^{-1} depicted in Fig. 8). The carried-out calculations showed the secondary gamma dose rate distribution is not significant especially far from the direct beam direction, which the values are less than 3 μSv.h^{-1} (Fig. 9).

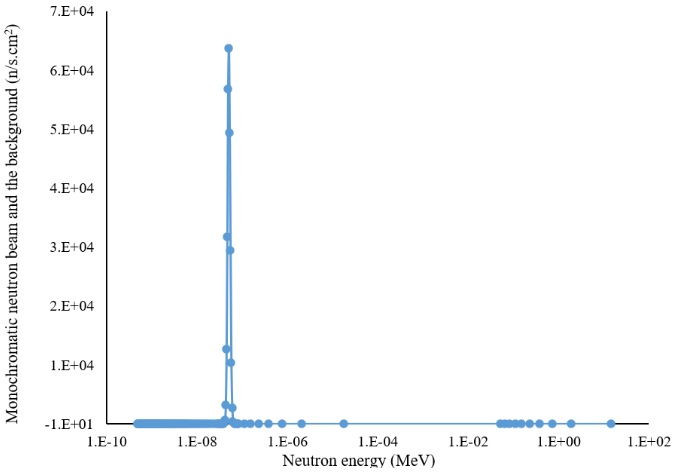

Figure 5: Neutron spectrum exited from the second collimator of TRR diffraction facility.

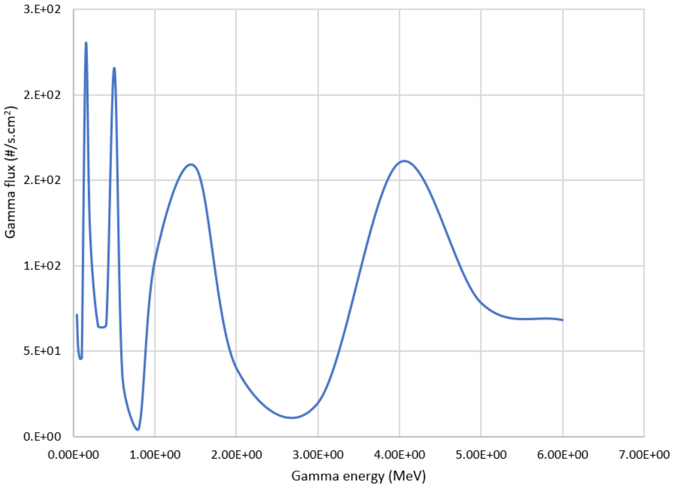

Figure 6: Gamma spectrum exited from the second collimator of TRR diffraction facility.

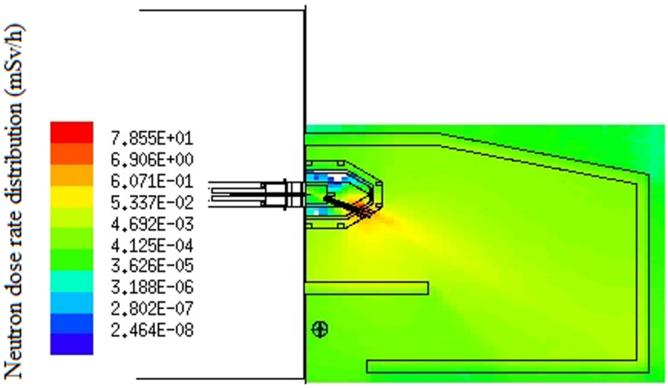

Figure 7: Neutron dose rate distribution inside the TRR diffraction laboratory room at 5 MW reactor operation.

Figure 8 shows the secondary gamma dose rate distribution near to the second collimator exit. As it is clearly observed from the figure especially far from the direct beam direction the values are less than 0.5 μSv.h^{-1} (Fig. 10).

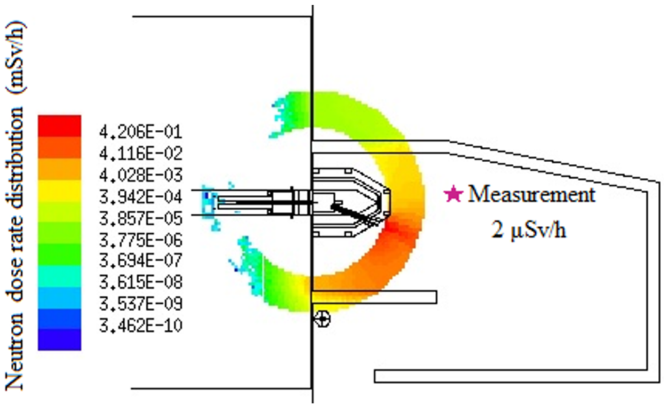

Figure 8: Neutron dose rate distribution near to the second collimator exit

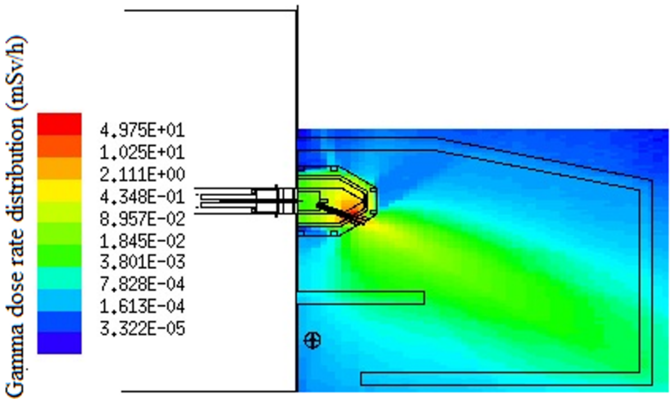

Figure 9: Secondary gamma dose rate distribution inside the TRR diffraction laboratory.

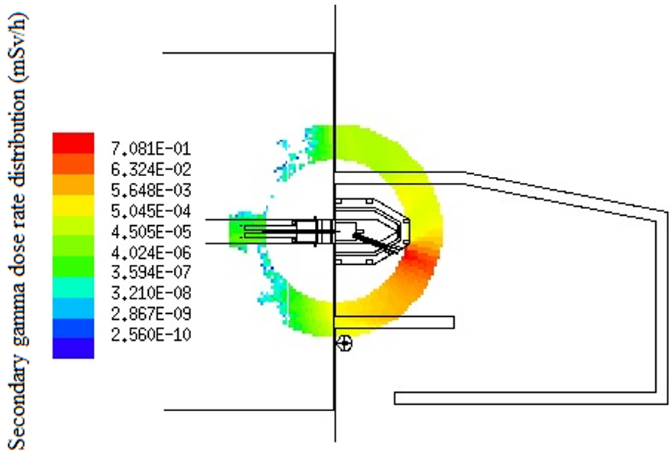

Figure 10: Secondary gamma dose rate distribution near to the second collimator exit.

The carried-out calculations showed if a 7%-borated polyethylene sheet with $(5\times6\times20\ \mathrm{cm}^3)$ dimension is used as a shutter inside the second collimator path after the second collimator end (the position could be seen in Fig. 2), the neutron dose rate would be less than 5 μSv.h^{-1} at the direct beam exit (Fig. 11).

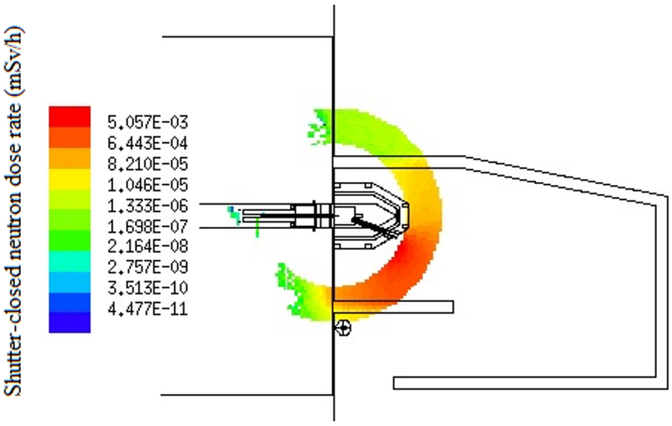

Figure 11: Neutron dose rate distribution near to the second collimator exit when the beam shutter is closed.

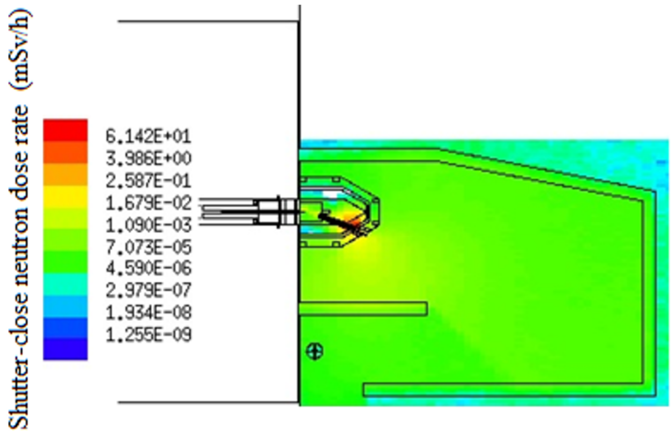

Figure 12: Neutron dose rate distribution inside the laboratory when the beam shutter is closed.

The neutron dose rate measurement at a distance 70 cm far from the second collimator exit showed in this situation, the neutron dose rate is 5 μSv.h^{-1} which is in good conformity with the carried-out simulations. The neutron dose rate distributions inside the laboratory in shutter-closed situation is presented in Fig. 12. As the figure shows, when the beam shutter is closed the laboratory neutron dose rates except near to the shutter are less than 1 μSv.h^{-1}.

Neutron and gamma dose rates were measured around the laboratory boundary at different points and depicted in Fig. 13. The measured values showed all the areas have a total neutron and gamma dose rate less than 3 μSv.h^{-1} except upper area; this area is near to B channel of TRR so these values belong to both D (diffraction facility) and B (rabbit system) channel dose rates. Moreover, the monochomator control-mechanic device electronic wire outlet is placed at this area so that would result in neutron/gamma leakage from the outlet which is not possible to be shielded tightly (called the control area). It should be mentioned the calculation errors were less than 5%.

Neutron and gamma dose rates were measured using LB6411 and LB1236 dosimeters respectively (Fig. 14). The repeatability errors of the used devices are 7% and 2.4% respectively.

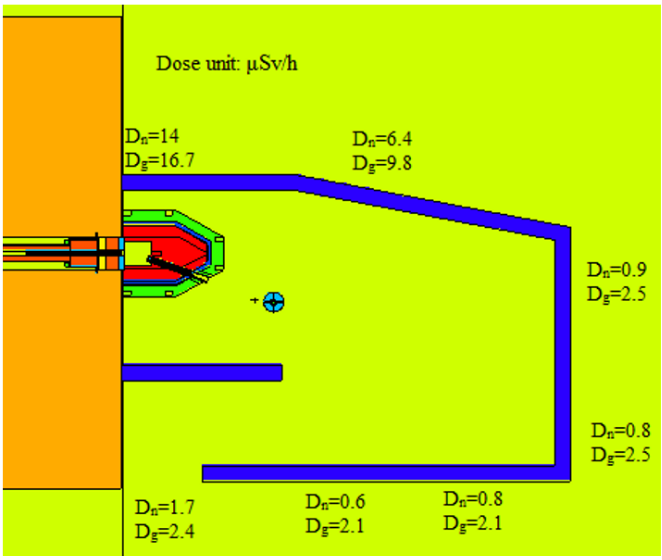

Figure 13: Neutron and gamma measured dose rates around the laboratory when the beam shutter is open and TRR is operated at 5 MW.

Figure 14: Neutron and gamma dosimeters used for the measurements (https://www.berthold.com/en/radiation-protection/products/).

4 Conclusions

Radial channels of research reactors have been equipped to different devices to provide neutron laboratories. In TRR, D radial channel of the research reactor has been equipped to different devices which provides monochomatic beam. The obtained beam is used for monochomatic neutron cross section measurement, studying diffraction patterns from different crystalline materials as well as other proposed applications. Dose rate mapping inside the laboratory helps to the users avoid high exposure areas during the work inside it. The present work carried out using MCNPX computational showed when the beam shutter of the facility is closed, inside the laboratory neutron dose rates are less than 5 μSv.h^{-1}. During the facility operation, again the neutron and gamma dose rates are less than 5 μSv.h^{-1} except the exited beam direction (from the second collimator of the facility shield). So, the users should avoid exposures of this area. Also, the simulations as well as the measurements showed when the laboratory is under use while the research reactor is operated at its full power (5 MW), summation of neutron and gamma dose rates are less than 3 μSv.h^{-1} around the laboratory boundary except the control area. Such dose rate mapping using the simulation method gives awareness to the users about the high-exposure regions and also about the proper placement of control systems of the facility at the least dose rate areas inside the laboratory room; for example, the electronic rack which the facility operator spends much time near it.

Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work.

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