Design of a thermal neutron beam for a new neutron imaging facility at Tehran research reactor

Mohammad Hossein Choopan Dastjerdi, Hossein Khalafi

Abstract

A new neutron imaging facility will be built around the Tehran Research Reactor (TRR). The TRR is an open pool light water moderated 5 MW research reactor with six beam tubes. The neutron energy spectrum near the reactor core at the entrance of the beam tube was measured by the foil activation method using the SAND-II code and calculated by the MCNP Monte Carlo code. There was a good similarity between calculated and simulated spectra. The principal component of this facility is its neutron collimator. The collimator is a beam-forming assembly which determines the geometric properties of the beam. In addition, it may contain filters to modify the energy spectrum or to reduce the gamma ray content of the beam. The optimum thickness of filters, the position of the aperture and other details of the neutron collimator were calculated using MCNP Monte Carlo simulations. In this design, the L/D ratio of this facility had the value of 120. The thermal neutron flux at the image plane was about $7.8 \times 10^6$ n/cm$^2$.s and n/$\gamma$ ratio about $10^6$ n/cm$^2$.µSv.

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1. Introduction

About 30 years ago, a neutron radiography facility was installed at the 5 MW Tehran Research Reactor (TRR) - Kamalimoghaddam and Tabatabaeian (1984). The measured neutron flux at the exit of the collimator is $4.42 \times 10^4$ n/cm$^2$.s with a Cd ratio of about 32. The relatively low neutron flux and some limitations in the object size and the

* Corresponding author. Tel.: +98-21-82064265; fax: +98-21-88221285.
E-mail address: mdastjerdi@aeoi.org.ir
space around the reactor reduce the applicability of these techniques and this facility is currently inoperable. To eliminate these limitations and to develop the use of neutron imaging techniques around TRR, a new neutron imaging facility was planned to be built. There are two choices: modification of the current neutron collimator and/or design and construction of a new neutron beam line.

In this paper, the design of a new neutron beam line has been completed. For this purpose, the “E” beam tube (north-west beam tube) of the TRR was selected (see Fig. 1) and the neutron energy spectrum was calculated and measured in this beam tube. The neutron beam line design (also including the filters and collimator) was simulated using the Monte Carlo MCNP code - Briesmeister (2000).

2. Neutron collimator design and simulation

The principal component of this facility is its neutron collimator. The collimator is a beam-forming assembly, which determines the geometric properties of the beam. In addition, it may contain filters to modify the energy spectrum or to reduce the gamma ray content of the beam. Bismuth (Bi) and sapphire (Al₂O₃) were examined as gamma and fast neutron filters respectively. The design study has been performed to meet the following objectives: an L/D of ~150 (D is the size of the aperture and L is the distance from the aperture to the image plane), a maximum neutron to gamma (N/G) ratio, a maximum thermal neutron content (TNC), and a uniform beam at the image plane. The collimator design, the optimum thickness of filters and other details of the collimator design were determined using MCNP simulations. Simulations were done in two stages. In the first stage, the TRR core calculation was performed to obtain the neutron and gamma energy spectra at the inlet of the “E” beam tube. The MCNP model of the TRR core and radial beam tubes is shown in Fig. 2.

Fig. 1. A schematic of the TRR showing the position of the core and irradiation facilities including the “E” beam tube.

Fig. 2. The MCNP model of the TRR core and radial beam tubes.
For verification of this simulation, the neutron energy spectrum was measured by the foil activation method using the SAND-II code. In the second stage of simulations, the transport of the neutron and gamma radiation incident on the “E” beam tube inlet through the filters and collimator up to the image plane was determined to achieve the design objective stated above. In this design, a 10 cm thick bismuth crystal is used for gamma attenuation and a 12 cm thick sapphire crystal is used to filter fast neutrons. The thickness of the bismuth filter is optimized for maximum N/G ratio. B$_4$C was selected as the aperture material with the thickness of 3 cm. The optimized position and diameter of the aperture is 120 cm and 3.5 cm respectively, corresponding to an L/D ratio of 120. The MCNP collimator design model is shown in Fig. 3.

![Fig. 3. The 3D MCNP model of the designed collimator.](image)

3. Results and discussion

The calculated neutron energy spectrum at the inlet of the “E” beam tube is shown in Fig. 4. In addition, for verification of the calculated data, the neutron energy spectrum at the inlet of the beam tube also was measured and is shown in Fig. 4.

![Fig. 4. Calculated and Measured neutron energy spectrum at the inlet of the “E” beam tube.](image)

There is a good similarity between the calculated and measured energy spectra. The inlet neutron energy spectrum has a peak around the thermal region (0.1 eV) and it is not necessary to add additional moderator. On the other hand, the fast neutron content of the incident spectrum is high and it should be filtered. In addition, the calculations showed the existence of a large gamma flux in the beam. This is because of the fact that the “E” beam tube has a direct view of the TRR core. To obtain a high N/G ratio and a high TNC, the use of fast neutron and gamma filters was necessary. A 12 cm thick sapphire crystal and a 10 cm thick bismuth crystal were used for fast
neutron and gamma ray filtering respectively. Fig. 5 shows the effect of various thicknesses of sapphire on fast neutron transmission.

As shown in Fig.5, a 12 cm thick sapphire crystal transmits only 3% of the fast neutrons and is, therefore, a very effective filter for fast neutrons. As previously mentioned, a 10 cm thick bismuth crystal is used for filtering the gamma rays. The calculated gamma dose rate at the outlet of the beam tube is 1113 Sv/h and this could be reduced to 75 µSv/h by using the bismuth filter. The overall collimator system (including filters and collimator) was simulated and the calculated parameters are listed in Table 1.

| Parameter                                | Value       |
|------------------------------------------|-------------|
| Neutron Flux at the image plane          | $7.8 \times 10^6$ n/cm$^2$.s |
| Thermal neutron content (TNC)            | Over 70%    |
| N/G ratio                                | $1.33 \times 10^6$ n/µSv.s |
| L/D ratio                                | 120         |

4. Conclusion

TRR is one of the most important neutron sources available in Iran. For development of neutron imaging applications in nondestructive testing, material science and engineering and industrial inspection, a preliminary study was carried out around TRR. The neutron energy spectrum was calculated (by simulation) and measured at the inlet of the “E” beam tube. A neutron collimator was designed and simulated and the main collimator and neutron beam parameters were calculated. All simulations were done using the MCNP code. In this design, a 12 cm thick sapphire crystal and a 10 cm thick bismuth crystal were used as fast neutron and gamma ray filters respectively. Results show that the main parameters of the neutron beam are suitable for a typical neutron imaging facility.

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