Monte Carlo simulation of an upgraded PGNAA shielding at TRR–1/M1

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Abstract. This paper describes the upgraded collimator and shielding design principle for the prompt gamma neutron activation analysis (PGNAA) facility at the Thai Research Reactor. The neutronic calculations with different geometry and material conditions are simulated using the Monte Carlo code. Then, the optimal parameters to maximize the thermal neutrons and minimize background radiations are obtained. The simulation result provides significant contribution in upgrading the PGNAA facility to be available in various applications.

1. Introduction

Prompt gamma neutron activation analysis (PGNAA) is a non-destructive and flexible analysis technique. The technique uses the prompt characteristic gamma-ray produced from the neutron inelastic scattering $(n,n'\gamma)$ and thermal neutron capture (n_{th},γ) reaction between incident neutron and element composition target. It has the advantage of using neutron capture prompt gamma-ray spectroscopy to analyse many elements which cannot be determined by conventional neutron activation analysis (NAA). Moreover, it allows for the analysis of many elements which do not produce sufficient amounts of activity to be measured with other elemental analysis techniques. PGNAA is becoming an important technique which has been implemented at a number of research reactors around the world [1–3].

Among the world wide PGNAA development and applications, the study of the PGNAA system in Thailand is ongoing. The system has been designed, built, and characterized at the Thai Research Reactor–1/ Modify 1 (TRR–1/M1) since 1989 [4]. The system was designed for the research reactor operating at 1.2 MW with the maximum thermal neutron flux and fast neutron flux at the centre of the reactor core of 3.1×10^{13} n.cm^{-2}.s^{-1} and 2.3×10^{13} n.cm^{-2}.s^{-1} respectively. The existing facility consists of a 6 inch diameter neutron beam port from the reactor core, beam shutter, gamma collimator, and biological shields as shown in figure 1. The total neutron fluxes at the sample position were obtained by measurement of the emitted gamma-ray from irradiating gold-foil via (n,γ) reaction using the LaBr$_3$ detector. The 1 mm thick of cadmium moderator have been applied to the detector to absorb the thermal neutron, thus the epithermal neutron fluxes have been measured. The thermal and epithermal neutron fluxes at the sample position are $4.63 \pm 2.15 \times 10^6$ n.cm^{-2}.s^{-1} and $4.43 \pm 1.13 \times 10^5$ n.cm^{-2}.s^{-1} respectively [5].

Since 2009, the construction of the existing system has been studied based on Monte Carlo simulations [5]. In addition, the high efficiency high purity germanium (HPGe) detector for the PGNAA at TRR-1/M1 has been calibrated [6]. The results show that the system at sample irradiated position and detector position suffered from the background radiation. Therefore, the work reported here considered the design of the collimator and shielding of a sample and detector. A series of the calculations of the collimator and shielding materials and dimensions have been carried out using the Monte Carlo code MCNP [7]. The upgraded collimator and shielding for the PGNAA facility is investigated and reported.

2. The detailed model and simulation results

The main components that have been designed in this work are the collimator, reflective material and detector shielding. The design is based on the existing PGNAA structure and the use of the neutron source from the reactor [5]. The uniform neutron source (disk source with a radius of 2 cm) consists of 3.1×10^{13} n.cm^{-2}.s^{-1} and 2.3×10^{13} n.cm^{-2}.s^{-1} of epithermal and fast neutron fluxes have been applied in the model. It is placed in the front of the collimator. The MCNP is used to perform the optimization process of the material

Figure 1. The PGNAA Facility at Thai Research Reactor.

and dimension of the collimator, moderator and shielding geometries. The aim is to minimize the contribution of the fast neutrons and γ-rays. The F5 tally was set at the sample area and at the detector position to measure neutron and gamma radiation. The details of the upgraded PGNAA structure are discussed in this section.

2.1. Collimator

Due to the high scattering cross section, the different models of polyethylene collimator have been modified in the MCNP model of the PGNAA (presented in Ref.[5]). The designed collimator is located behind the existing beam shutter to collimate the neutron beam toward the sample as shown in figure 2. As the figure illustrates, the cone collimator has a length of 27 cm and aperture diameter of 3.68 cm and 6 cm. By adding the collimator in the model, the thermal neutron flux (Φ_{th}) has been

Figure 2. The model of the PGNAA collimator.

improved from 3.3476×10^6 n.cm^{-2}.s^{-1} to 7.6215×10^6 n.cm^{-2}.s^{-1} which resulting the ratio of flux thermal to flux fast (Φ_{th}/Φ_f) increases from 8.65 to 11.43. The results show that the thermal neutron fluxes increase significantly by using the collimator.
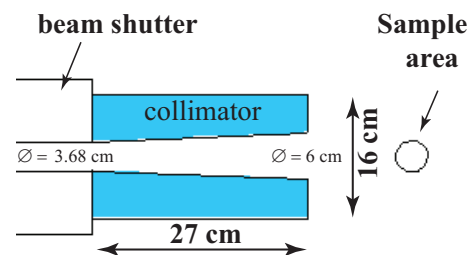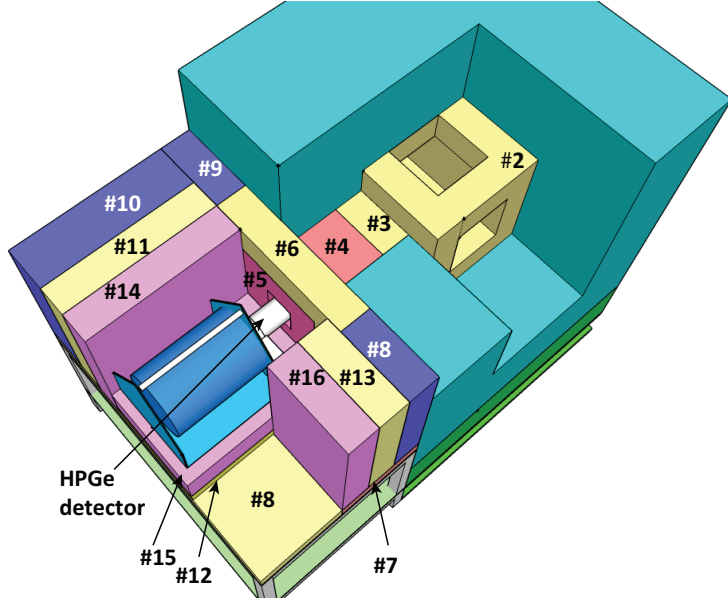
2.2. Shielding

The primary criteria for the shielding design at the detector position are to reduce the γ-ray background from the irradiation area and to protect the detector from damage due to neutron radiation. The different materials have been selected as shown in figure 3. The inner shielding

has been designed to shield fast neutrons using the 7.5% lithium polyethylene (LiPE) with density of 1.06 g/cm^3 as depicted in yellow (#2 and #3) in figure 3.

The model have been modified based on the existing 30 cm thick biological shield which is filled with steel shots and paraffin. Due to the high neutron absorption cross section, the first lithium polyethylene box is located inside the biological shielding with a thickness of 10 cm. A 20 cm × 20 cm hole is designed at the top of biological shielding for sample holding. A 10 cm × 10 cm hole is added to collimate the prompt γ-rays toward the detector. The ring detector tallies and point detector tallies are used to measure radiation at the irradiation area and detector position respectively. The next layer is the detector shielding.

#2, #3, #6, #11, #12, #13	7.5% Lithium polyethylene (LiPE)
#4, #5, #7, #14, #15, #16	Lead
#8, #9, #10	5% Boron loaded polyehylene (BPE)

Figure 3. Illustration of the designed shielding.

It consists of different materials layers from the irradiation area toward the HPGe detector. The shields and the materials used are depicted with label number and color in figure 3. The lead is used to shield the background γ-rays from the surrounding structure. Moreover, to prevent the detector from the high neutron flux, the 5% boron loaded polyethylene (BPE) was selected due to its high neutron absorption as depicted in purple in figure 3. The prompt γ-ray collimator has been designed to fit the detector with the dimensions of 10 cm × 10 cm.

The simulated neutron and gamma spectra have been obtained. The flux at the irradiation and detector positions were separately measured for each shielding layer as presented in table 1. The background γ-rays at the detector with and without shielding are shown in figure 4. With the shielding, there was a decrease of two orders of magnitude in background γ-rays.

2.3. Moderator

The efficiency of the PGNAA system is improved with the number of the thermal neutron fluxes at the irradiation area. However, the fast neutrons (so-called background radiation) remain a problem. Theoretically, the fast neutron can be moderated to the thermal neutron by the moderator material. Therefore, the
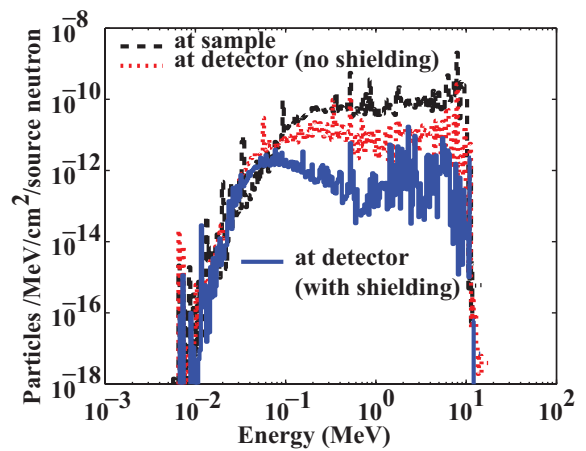

Figure 4. The gamma spectra at sample area (without shielding) and at the detector position (with and without shielding).

increased number of the thermal neutrons can be achieved using the moderator in the model. Five moderator materials have been chosen: H_2O, D_2O, paraffin, polyethylene and graphite due to the high cross section of (n,n') reaction. The moderators have been designed to fit the collimator model in figure 2 with different thickness between 5 cm and 27 cm along the collimator. The neutron and gamma fluxes are obtained and the best choice of the moderator will be optimized. Figure 5 shows the calculated results for the five chosen moderator materials. The thermal neutron fluxes were constant with increasing H_2O, paraffin and polyethylene thickness and decreased with increasing D_2O and graphite thickness as shown in figure 5(a). Figure 5(b) shows that fast neutron fluxes reduced about two orders of magnitude by using paraffin. Therefore, the value of Φ_{th}/Φ_f increased when the thickness of paraffin increased.

Table 1. Radiation fluxes at sample and detector position.

| Shielding	at sample (n.cm^{-2}.s^{-1})		at detector (n.cm^{-2}.s^{-1})		
	Φ_{th}	Φ_f	Φ_{th}	Φ_f	Φ_γ
no shielding	7.6259E+06	6.6800E+05	1.8309E+05	946.2975	1.1508E+05
#2, #3	7.8058E+06	6.6863E+05	1.8432E+05	984.8532	1.1204E+05
#4, #5	7.8064E+06	6.6846E+05	1.8684E+05	942.4790	2.5265E+04
#6	7.8033E+06	6.6865E+05	1.7289E+05	719.2019	2.3945E+04
#7	7.8029E+06	6.6861E+05	1.7308E+05	640.8303	2.1241E+04
#8	7.8040E+06	6.6863E+05	1.5743E+05	562.2896	2.3802E+04
#9, #10	7.8049E+06	6.6861E+05	1.4699E+05	553.3937	3.5392E+04
#11, #12, #13	7.8070E+06	6.6850E+05	1.3155E+05	492.3617	3.9263E+04
#14, #15, #16	7.8064E+06	6.6853E+05	1.2588E+05	514.2746	1.1360E+04
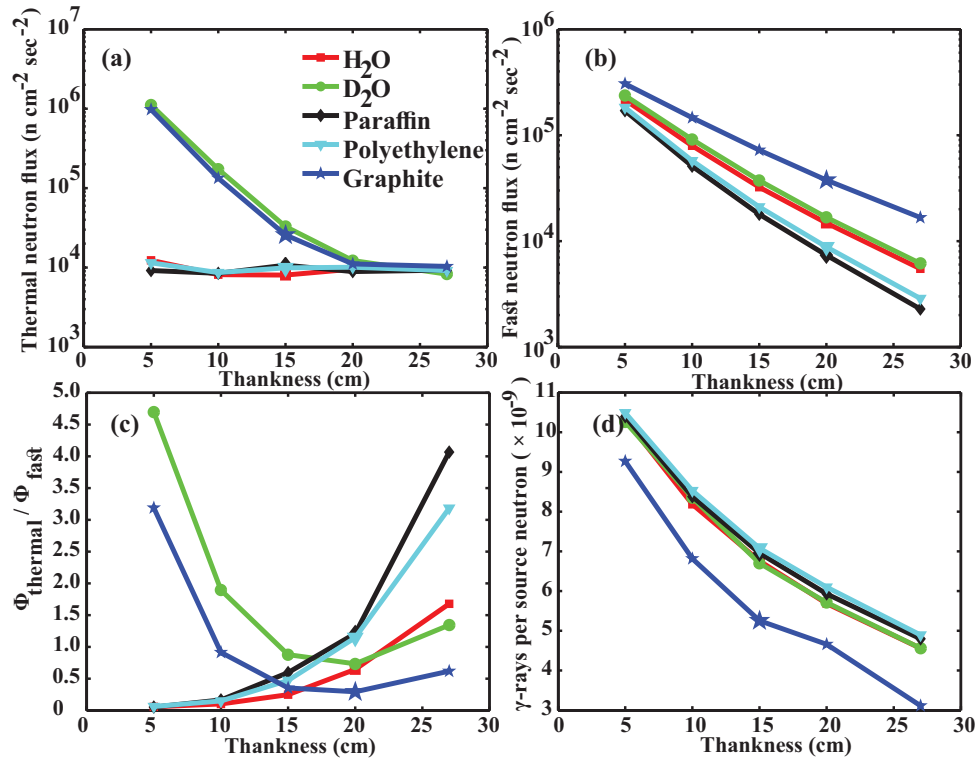
Figure 5. The thermal neutron flux of five moderator materials with different thicknesses at the irradiation area.

Due to the (n,γ) reaction of the moderator materials, γ-rays are generated. The results in figure 5(d) show the number of γ-rays generated by different moderator thicknesses. Graphite produced lowest background γ-rays. However, due to the high thermal neutrons and low fast neutrons generation, paraffin is suggested for the moderator in this work.

3. Discussion and conclusion

The newly designed collimator and shielding for the PGNAA facility at TRR-1/M1 have been studied using the MCNP calculation and we suggest that they are adopted by the PGNAA facility. The facility has a thermal neutron flux of 7.8064×10^6 n.cm^{-2}.s^{-1} at the sample irradiated area. The fast neutron flux and background γ-rays are significantly reduced by using the proposed shielding and moderator. The work reported in this paper provides a significant contribution towards upgrading the PGNAA station at the Thai Research Reactor to enhance its availability in various applications and techniques of elemental technique.

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