NEUTRON FLUX MEASUREMENTS IN THE ROTARY RACK OF THE REAKTOR TRIGA PUSPATI

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ABSTRACT

Neutron flux is an essential parameter in evaluating the performance of research reactors. The neutron flux distribution in the core region of the Reaktor TRIGA PUSPATI (RTP) has been measured through the neutron activation analysis method, using bare and cadmium covered gold wires activation. The aim of the measurement is to determine the neutron flux in the rotary rack at the end-of-cycle (EOC) RTP core-15. The wires were irradiated in the rotary specimen rack with the reactor operated at 750 kW. The gamma activities of the wires are measured by using high-purity germanium (HPGe) gamma detector.

ABSTRAK

Fluks neutron merupakan parameter penting dalam penilaian prestasi sesebuah reaktor penyelidikan. Taburan fluks neutron terma di dalam teras Reaktor TRIGA PUSPATI (RTP) diukur melalui teknik analisis pengaktifan neutron menggunakan pengaktifan wayar emas dan wayar emas dilindungi rod kadmium. Objektif pengukuran ini ialah menentukan nilai fluks neutron di rak berputar di penghujung kitaran konfigurasi teras RTP yang ke-15. Eksperimen dijalankan di fasiliti penyinaran rak berputar dengan kuasa reaktor 750 kW. High-Purity Germanium (HPGe) Gamma Detector digunakan untuk pengukuran aktiviti gamma wayar yang disinarkan.

Keywords: neutron flux measurement, TRIGA PUSPATI, rotary rack, reactor technology

INTRODUCTION

Neutron flux in a nuclear research reactor is distinguished into three regions based on its kinetic energy values, either thermal, epithermal or fast neutron flux. The accurate measurement of the neutron flux distribution in a research reactor is basic to almost every experiment in reactor physics, activation analysis and others. Therefore, the neutron flux is an essential parameter to be determined when evaluating the research reactor performance.

Accurate measurements of the neutron flux are required for verification of the core design, calibration of the fission power and others, such as in the new research reactor commissioning [1,2,3]. The measurement of the neutron flux distribution is conducted in [4] to check the reliability of predictions of the power distribution at designated reactor power to provide basic data for the safe and reliable reactor operation. Neutron flux measurements are commonly helping in decision making of the reactor routine in-core fuel management activities.

The determination of neutron flux at any irradiation facility is an important key factor for designing an appropriate neutron beam [5]. It can be achieved in form of simulations or experimental approaches. Some works in other TRIGA reactors can be found in [6,7,8].

In this paper, neutron activation measurements were performed to map the neutron flux in the reactor core region. The experiments were conducted on the Reaktor TRIGA PUSPATI (RTP) at Malaysian Nuclear Agency that have been serving as neutron source for various application in the fields of basic nuclear research and education since 1982. To date, RTP core has been reshuffled 15 times to maintain safe operation and fulfilling the neutron research demand in nuclear technology. The aim of this study is to determine the neutron flux at the RTP irradiation facilities especially in the rotary rack at the end-of-cycle (EOC) RTP core-15. The results will complement other RTP neutronic calculations and simulations presented in [9,10,11]. To determine the neutron flux, bare and cadmium-covered gold wires were irradiated in a rotary specimen rack with the reactor operating at the steady state power of 750kW. The gamma activities of the wires are measured by using high-purity germanium (HPGe) gamma detector.

PUSPATI TRIGA REACTOR – BRIEF BACKGROUND

RTP is the TRIGA MARK II pool-type light water reactor cooled by natural convection and moderated by demineralized light water. The fuel element is a solid, homogeneous mixture of uranium zirconium hydride alloy containing about 8.5%, 12% and 20% by weight of uranium enriched to 20% in U-235. The power level of the reactor is controlled by four control rods made up of boron, namely Regulating, Safety, Shim and Transient. It has an annular core surrounded by graphite reflector.

The first operational core in 1982, known as Core-01, consists of 86 8.5% fresh fuels. The core excess reactivity around $7.00 and was successfully operated for several years with maximum power of 1MWth. To maintain safe operation and fulfilling the local neutron research demand, the reactor core is reshuffled from time to time. After 40 years of operation, the fuel elements in RTP core has been reshuffled 15 times. The current Core-15 consists of 8.5 wt.%, 12 wt.% and 20 wt.% fuel elements, four control rods and graphite elements is approaching its seventh year of operations. The present core's core excess reactivity was $ 4.43 (for updated burnup up to December 2020), and the control rods' reactivity worth is sufficient to allow total control of the reactor during operation from shutdown to full power [12].

The in-core irradiation fasilities available at RTP are rotary rack, instrumental delayed neutron activation analysis system (IDNAA), pneumatic transfer system (PTS) and dry tube (DT). A rotary rack has about 40 positions specimen rack that can accomodate about 80 samples simultaniously. It is commonly used for radioisotope production and small samples activations. On the other hand, a pneumatic transfer system suitable for short periods irradiations in which the samples will be in the reactor core for a short-designated time and then ejected. Other fasilities would also have diverse samples characteristic, experimental setting and research purposes due to different flux distributions and locations.

METHODOLOGY

Neutron flux measurements was obtained using neutron activation analysis technique. This technique focuses on determining the isotropic concentrations in pure elements or elemental concentrations in a compound or mixture. The target concentration can be determined using the known flux and measured activity. Meanwhile, the same technique can be applied to measure the unknown flux with known target concentration. This principle is used to characterize the neutron flux in nuclear reactors.

In measuring the neutron flux, two objectives need to be fullfilled. First is to determine the efficiency calibration curve for different source-detector distance using high pure germanium detector at Au-198 gamma energy photo peak and specific activity of activated samples. Second is to determine the neutron flux distribution at the in-

core irradiation facilities especially in the rotary rack by using activated Aurum-bare (Au-bare) and Aurum-Cadmium (Au-Cd) wires.

Irradiated Au-Bare is exposed to neutron of all energies. The total activity of the bare wire is the sum of two terms representing the neutron contributions of the two energy ranges: thermal and epithermal

$$A_b = A_{th} + A_{epi} \tag{1}$$

A cadmium filter of 0.5 to 1 mm thick absorbs nearly all neutrons below 0.4 eV, and few neutrons above about 0.6 eV. Thus, it is convenient to describe the Au-Cd activations in terms of an effective cadmium cutoff energy E_{Cd} near 0.5 eV, and a cadmium filter correction factor F_{Cd} which is the ratio of the epithermal activation from neutrons above E_{Cd} in Au-Bare, to the measured activation with Au-Cd. The evaluation of E_{Cd} and F_{Cd} involve the neutron spectrum and angular distribution, the cross section, thickness and shapes of the wire and the cadmium filter.

Then, the epithermal activation is given by:

$$A_{epi} = F_{Cd} + A_{Cd} \tag{2}$$

The cadmium ratio, R_{Cd}, is defined as the ratio of the activity of Au-Bare, A_b, to the activity of identical wire Au-Cd, A_{Cd}:

$$R_{Cd} = \frac{A_b}{A_{Cd}} \tag{3}$$

The thermal activity can be obtained from equations (1), (2) and (3) [13]:

$$A_{th} = A_b \left(1 - \frac{F_{Cd}}{R_{Cd}}\right) \tag{4}$$

The thermal activity and the flux are related through the equation:

$$A_{th} = N\sigma\Phi_{th} \tag{5}$$

which can be implemented as:

$$\Phi_{th} = \frac{A_{th}}{N\sigma\left(1-e^{-\lambda t_{irr}}\right)};\ \Phi_{epi} = \frac{A_{Cd}}{N\sigma\left(1-e^{-\lambda t_{irr}}\right)};\ \Phi_{total} = \frac{A_b}{N\sigma\left(1-e^{-\lambda t_{irr}}\right)} \tag{6}$$

where A_{th} is specific activity of Au-bare minus specific activity of Au-Cd, A_{Cd} is specific activity of Cd, A_b is specific activity of Au-bare, N is Avogadro's number, λ is decay constant, σ is the cross section of Au-197 and t_{irr} is irradiation time in second.

Specific activity calculation using equation:

$$A_b, A_{b+Cd} = \frac{\lambda\left(\frac{net\ peak\ area}{mass}\right)}{\varepsilon\gamma\left(e^{-\lambda t_{decay}}\right)\left(1-e^{-\lambda t_{measure}}\right)} \tag{7}$$

where λ is the decay constant of the nuclide, ε is the efficiency of the detector, γ is the intensity of Au, t_{decay} is the time decay during cooling and $t_{measure}$ is the time decay during irradiation.

EXPERIMENTAL PROCEDURE AND RESULTS

Neutron flux and energy spectrum measurements require an assortment of neutron activation wires and threshold detectors as well as counting equipment to the level of sophistication desired. Prior to irradiations, activation samples were prepared in a form of Au-bare and Au-Cd such as presented in Figure 1. Activation wires were cut between the range of 0.5 to 1.0 cm length, while the Cd tube were cut approximately 2 cm length. Each of them was weighted and recorded accordingly. Some wires then carefully inserted into the Cd tube and tightly sealed using pliers, to be the Au-Cd samples. All Au-bare and Au-Cd wires were put into the vials, sealed and labled before inserted into the sample container suitable for the designated irradiation facilities as shown in Figure 2.

Figure 1: Sample preparations for Au wire (left) and Cd tube (right).

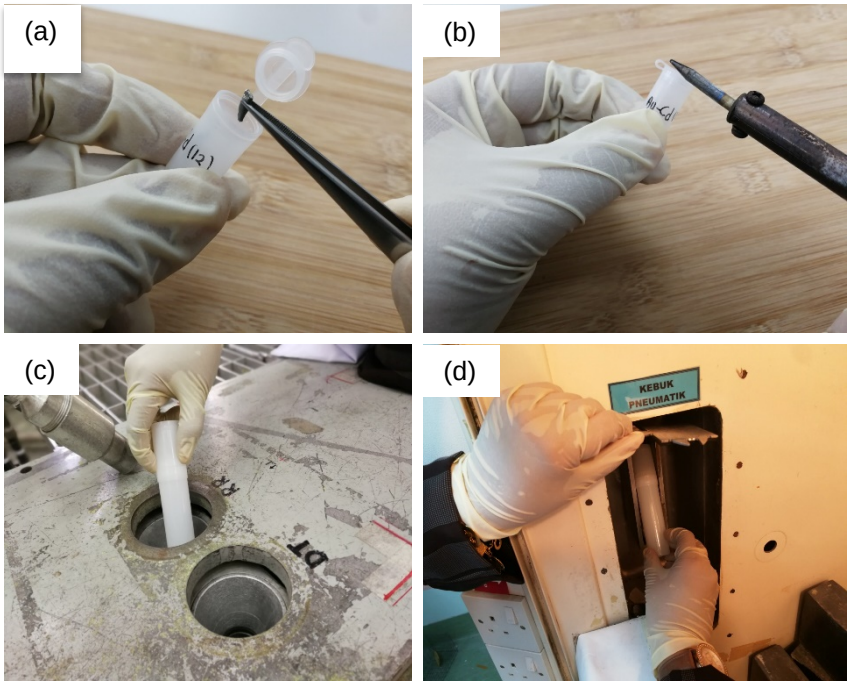

Figure 2: (a) Sample inserted into vials, (b) Vials were sealed to secure the samples, (c) Sample for irradiation in rotary rack and (d) Sample for irradiation at PTS.

All the samples were irradiated at power level of 750 kW in the range of 1 - 15 minutes based on suitability of irradiation time and samples handling process. After the completion of the irradiation, the samples were left inside the shielding container. There was a waiting time before the counting procedure started to allow the dose exposure rate of the samples decreased until it reaches an acceptable level to be handled and analyzed.

To obtain accurate results, it is essential to determine the efficiency of the detector prior to the analysis of the samples. The efficiency of detector was determined at geometry of 15 cm by using the Am-241, Ba-133, Cs-137 and Eu-152 for one hour. These standard sources were used as their energy ranges are within the kinetic energy range for Au. Once the detector efficiency is determined, Au-bare and Au-Cd samples were fixed horizontally facing the center of the detector for 10 minutes, while the detector dead time was kept below 20%. The detector, sources and sample position are shown in Figure3.

The detector efficiency was calculated using equation:

$$Efficiency, \varepsilon = \frac{Net\ area}{(Live\ time)(Activity)(yield)} \quad (8)$$

The result of efficiency calculation and its calibration curve is presented in Table 1 and Figure 4, respectively. Based on the equation from the plotted graph, the efficiency of detector, ε is 0.00288 for Aurum-198 with gamma energy 412 keV.

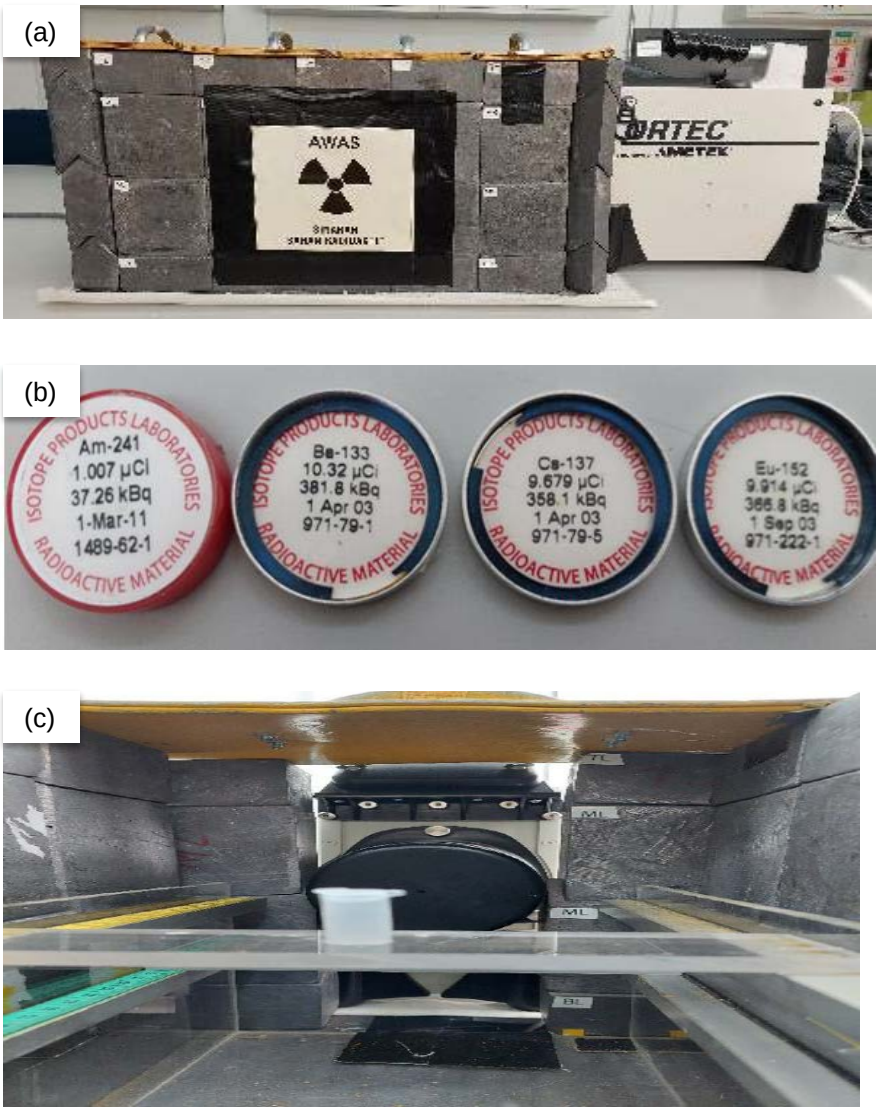

Figure 3: (a) High-purity germanium (HPGe) gamma detector used for the wires gamma activities measurement, (b) standard sources used for determination of detector efficiency and (c) sample position for counting.

Table 1: Detector efficiency calculations.

Nuclides	Energy (keV)	Efficiency
Am	59.67	1.99501E-03
Ba	81.02	3.25075E-03
Eu	121.84	3.99647E-03
Ba	303.19	2.65195E-03
Eu	344.62	2.36278E-03
Ba	356.36	2.32665E-03
Eu	411.49	2.05150E-03
Cs	661.66	1.34809E-03
Eu	779.48	1.20241E-03
Eu	964.6	1.01283E-03

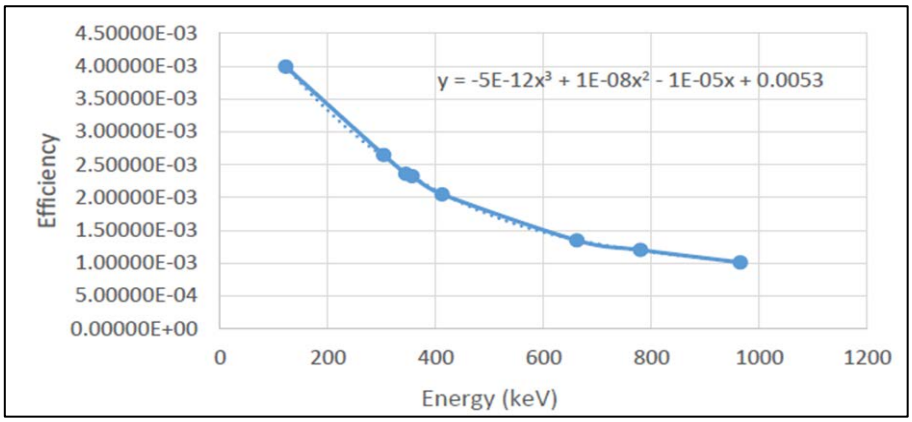

Figure 4: Efficiency calibration curve

Figure 5 and Table 2 represent the results of neutron flux measurement in the rotary rack considering its bottom and upper part. Based on the results, the thermal flux is higher than epithermal flux at both areas (bottom and upper part) of rotary rack irradiation facility. The bottom part of the rotary rack has higher thermal flux than the upper part. The rotary rack should be kept spinning to ensure irradiation samples interact with the same amount of neutron population.

Table 3 shows the results for neutron flux measurement at other in-core irradiation facilities. Thermal flux at IDNAAA Bare, PTS and DT were found to be higher than thermal flux in the rotary rack. The effect of cadmium material that has been used to capsulated the IDNAA Cd irradiation tube are also noticeable where the epithermal flux value was found to be greater than thermal flux value. The neutron flux value at PTS was lower compared to other in-core irradiation facilities since the facility was installed at the edge of nuclear reactor core.

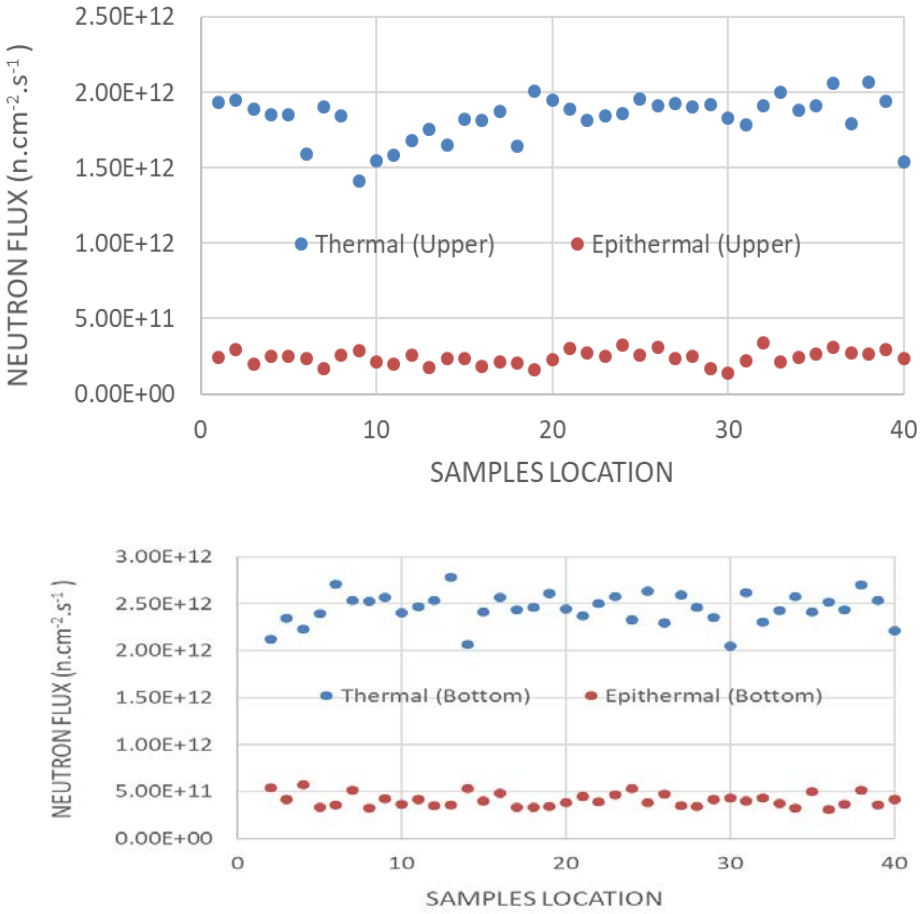

Figure 5: Neutron flux measurement in the rotary rack.

Table 2: Neutron flux in the upper and bottom part of the rotary rack.

Location	Neutron flux ($n.cm^{-2}.s^{-1}$)	
Rotary Rack	Thermal	Epithermal
Upper	1.413×10^{12} to 2.067×10^{12}	1.366×10^{11} to 3.378×10^{11}
Bottom	2.047×10^{12} to 2.707×10^{12}	3.105×10^{11} to 5.712×10^{11}

Table 3: Neutron flux measurement at other in-core irradiation facilities.

Location	Neutron flux ($n.cm^{-2}.s^{-1}$)	
	Thermal	Epithermal
IDNAA Bare	6.999×10^{12}	1.511×10^{12}
IDNAA Cd	1.621×10^{11}	9.217×10^{11}
PTS	3.310×10^{12}	5.733×10^{11}
DT	5.577×10^{12}	7.847×10^{11}

CONCLUSIONS

The accurate measurement of flux density is essential basic to almost every experiment in research reactor. The neutron flux of RTP was measured by the neutron activation method, using bare and cadmium-covered gold wires. Both bare and cadmium-covered gold wire samples were irradiated in the rotary rack and other in-core fasilities including IDNAA, PTS and DT, with the reactor power at 750kW. Their gamma activities were measured using HPGe detector with the efficiency of 0.00288. The detector efficiency was determined prior to the neutron flux measurement using Am-241, Ba-133, Cs-137 and Eu-152 at geometry 15 cm.

The average thermal neutron flux obtained in the rotary rack at 750kW was 2.0×10^{12} $n.cm^{-2}.s^{-1}$. In general, the thermal neutron flux profile is greater at in-core irradiation facilities located at the central of core region such as IDNAA and DT compared to PTS and rotary rack that located near the edge of reactor core. The effectiveness of cadmium material to shield thermal flux was significantly shown at the IDNAA Cd result. The results from these experiments would contribute to the RTP neutron profiling database and significant for the new core configuration (core-16) plan.

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