MEASUREMENT AND CALCULATION OF NEUTRON FLUX DISTRIBUTION IN KARTINI REACTOR USING SELF-POWERED NEUTRON DETECTOR (SPND) AND MCNPX CODE

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Submitted: 07 November 2023
Revision Received: 14 November 2023
Accepted: 26 April 2024
Published: 19 August 2024

DOI :
10.17146/jstni.2024.25.2.17

Keywords: *neutron flux, SPND, gold foil activation, MCNPX, sensitivity*

Abstract *The neutron flux is one of the important parts of the fission reaction. Recently, the fuel configuration at the Kartini reactor has been changed, and now it has 71 fuel elements. SPND has small cladding so this detector can reach a narrow gap in-core area. The output of SPND is a very small electric current. To convert from electric current to neutron flux, the value of the detector sensitivity is required, for this purpose, it is done by neutron flux measurement using gold foil activation method at the same location as SPND detector. MCNPX simulation is calculated through scanning area at the axial and radial direction from ring central thimble (CT), H7, H10, H12, H14, and H16. Using the Visual Editor (Vised) module of the MCNPX, the location of SPND measurement can be performed by MCNPX version 2.6.0, and nuclear data was used in ENDF/B-VI. The amount of axial data difference between SPND and gold foil activation measurements for location H16 is 8%. The trend of the graphs between SPND measurements and MCNPX simulations axially and radially are almost the same. However, there are differences in the data between the two. Such differences are caused due to the fact that the detectors are not modeled in MCNPX but using tally F5 instead. SPND data and gold foil activation at location H16 have almost the same neutron flux value for axial direction. This is a reference that the SPND detector is in good condition and valid for use.*

INTRODUCTION

Kartini reactor reached criticality on January 25, 1979. It has an operating power of 100 kW for research, irradiation, education, and training (1). Kartini reactor is classified as TRIGA MARK II type, with the current fuel configuration using 69 pieces of type 104 fuel and 2 pieces of type 204 fuel. The fission reaction that occurred in the core affected variation in neutron flux year by year. One of the factors influencing the changed value neutron flux is fuel burn-up. According to Hasni Handayani, burn-up is defined as the total energy that is released as the fuel burning per initial fuel mass unit (2). The value of neutron flux must be known for each irradiation facility in order to be able to select and manage the utilization of each irradiation facility according to the required analysis needs. One of the most important aspects of operational safety in a reactor is the neutronic aspect, which encompasses numerous parameters such as neutron flux, effective neutron multiplication factor, power peaking factor, and core excess. Neutronic parameters of reactor operation, in principle, will support the safety evaluation of the research reactor (3). In this context, many reactor operators and research practitioners have made efforts to measure and develop new techniques for neutron flux measurement (4,5). The neutron flux within the reactor core is highly dependent on the position and duration of reactor operation. Therefore, measuring neutron flux distribution within the core at various positions is crucial. Measurement of neutron flux distribution will be utilized for fuel management strategies and conducting experiments within the reactor core. In this research, neutron flux measurements are performed using Self-Powered Neutron Detectors (SPND), which provide an electrical current output.

Prior study, the sensitivity of SPND has been obtained. The present research focuses ’on measuring the neutron flux experimentally, both with gold foil activation and SPND, as well as developing models and calculations with MCNPX.

This research aims to study neutron flux distribution inside the Kartini reactor core with various methods, including measurement and calculation. The measurement data was obtained using SPND, and the calculation was performed using MCNPX code. Gold foil activation was also performed to calculate the SPND's neutron flux data. MCNPX calculation was compared with SPND measurement.

EXPERIMENTAL SECTION

This research was conducted at the Kartini reactor facility. This research requires various methods to obtain valid data. The security and safety aspects of this research are highly considered and follow the procedures in place at the facility.

Materials and Instrumentation

In this study, the research used the facilities of the Kartini reactor, which was set at 100 kW. This SPND detector has been used in previous research by Sofia Mubarika et al. (6), where in the study, the SPND calibration results have a linear regression equation as follows $\emptyset=4.57 \times 10^{20}\ I-2.74 \times 10^{11}$. SPND used as a detector is connected to a picoAmmeter so that it can be read how much electric current the detector produces due to its interaction with neutrons. To calculate the detector reading, an indirect measurement of neutron flux is needed by activating the gold foils. After being activated for 1 minute in the Kartini reactor core, the bare and wrapped cadmium samples will be counted using a GM detector that has been adjusted to the working voltage using a power supply. Simulation with MCNPX is used to predict how much total neutron flux value at the experimental site.

Methods

The experiments include the measurement of neutron flux by SPND for detector calibration using gold foil activation in the central thimble (CT) ring. The neutron flux is the number of neutrons crossing the unit area of the medium per second. The neutron flux is calculated by (7).

$$\varphi = nv \qquad (1)$$

where n is the neutron density (n/cm3), and v is the neutron speed (cm/s).

Recently, there have been 71 fuel elements in the Kartini reactor core. Two types of fuel elements are used, i.e., type 104 and type 204. Figure 1 shows the schematic of those fuel elements.

The difference between fuel elements type 104 and 204, based on Figure 1, is that in fuel element type 204, there is a sensor or instrumentation equipment used to measure fuel temperature called instrumented fuel element (IFE) (8).

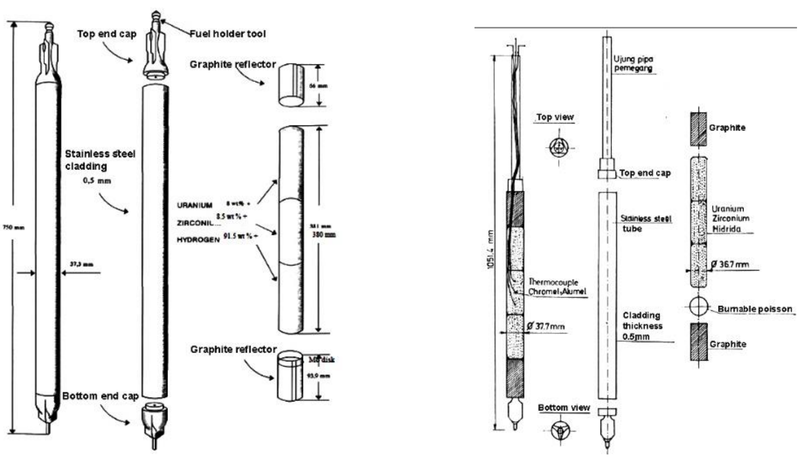

Figure 1. Fuel Element: a. 104 Type b. 204 Type

The neutron flux was measured when the reactor reached the intended power level of 100 kW. In this study, neutron flux is categorized into 3 energy groups, namely neutron energy group 1 with energy range <0.53 eV, neutron energy group 2 with energy range >0.53 eV, and total neutron flux is sum of the neutron energies of groups 1 and 2. The output of SPND is read by picoAmmeter as an electric current. For axial data, the SPND has to move every 10 cm until it reaches 40 cm from the top grid of the plate core, and for radial data, this detector is shifted from ring F to the central thimble ring. Neutron activation by using gold foils are mostly produced by neutron capture and commonly decays with emission of γ-rays (9). Gold foil activation is used for detector calibration. There are two gold samples, one of which is covered by cadmium (Cd), and then they are irradiated at the middle level of the central thimble core for 1 minute at the reactor power of 100 kW. The value of the neutron flux can be determined according to equation 2.

$$\emptyset = \frac{\lambda C \rho}{\kappa \Sigma_{act} m (1 - e^{-\lambda t_i}) e^{-\lambda t_d} (1 - e^{-\lambda t_c})} \quad (2)$$

where λ is the decay constant, C is the number of counts, ρ density of gold foil sample, ∅ is the neutron flux (n $cm^{-2}s^{-1}$), Σ_{act} is the macroscopic activation cross-section, κ is a constant or detector efficiency, t_i is the irradiation time, t_d is the delayed time before counted, t_c is the time count, and m is the mass of the gold sample. Several factors influence neutron flux, one of which is the cadmium ratio. The cadmium ratio (Fcd) is defined as the ratio of the bare to cadmium-covered foil activity (10). The cadmium ratio equation is shown in equation 3.

$$Fcd = \frac{\emptyset\ bare}{\emptyset\ cd} \quad (3)$$

In this experiment, gold foil activation was carried out to calculate the measurement results from SPND. Gold foil activation uses a dummy fuel element that has a stick diameter of 6 mm, and there are 4 sample placement points. A picture of the stick used for this research can be seen in Figure 2.

SPND commonly has two conductive electrodes as a coaxial structure, i.e., the emitter and the collector. Magnesium Oxide (MgO) or Alumina (Al_2O_3) is a mineral material considered between the electrodes as an electrically insulated space, where it aims to avoid direct recombination of the collected electric charges (11). This experiment uses SPND with Rhodium (Rh) as an emitter. SPND specifications are shown in Table 1.

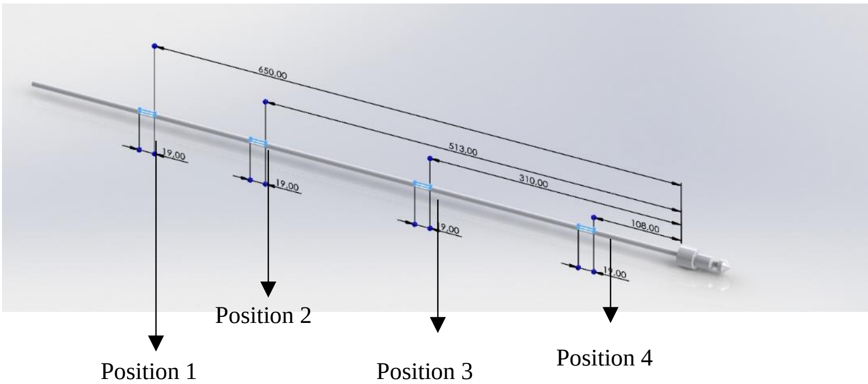

Figure 2. Stick for gold foil activation

Table 1. SPND specification (11)

Components	Material	ρ (g/cm^3)	R_{in} (mm)	R_{out} (mm)
Emitter	^{103}Rh	12.41	0.00	0.230
Insulator	Al_2O_3	3.569	0.230	0.535
Collector	Inconel-600	8.44	0.535	0.785

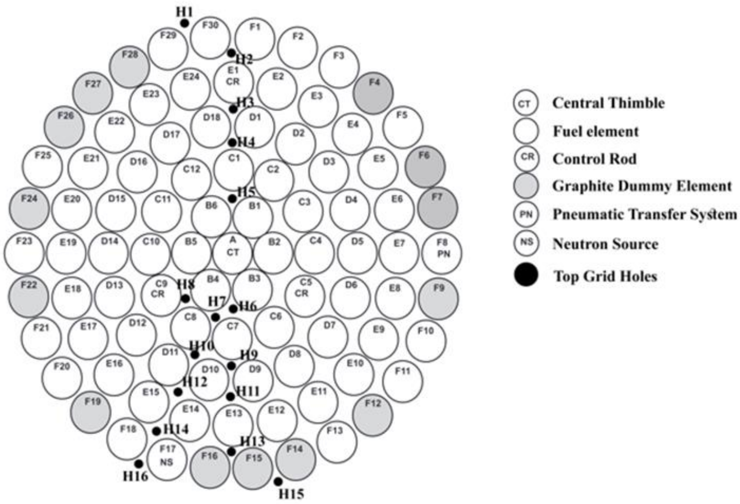

Figure 3. Kartini reactor core configuration

The interaction of SPND with neutrons produces an electric current proportional to the number of interactions. The signals detector from SPND are proportional to neutron flux but rather to neutron interaction (12). The output needs to consider the correction factor to be able to know the actual value (13). SPND's response time is depends on half life of β decay after neutron capture in emitter (14). The Kartini reactor core configuration is shown in Figure 3.

In this research, SPND was put into H16, H14, H12, H10, H7, and CT. These top grid holes represent the average neutron flux in each ring inside the reactor core. Measurements were taken when the reactor power reached 100 kW. Gold foil activation is the first important step to determine the sensitivity of SPND. SPND sensitivity calculation using equation 4,

$$S = \frac{I}{\emptyset \times L} \quad (4)$$

where I is current generated by SPND due to neutron reaction, ∅ is neutron energy of group 1, and L is SPND rhodium emitter length (8.5 cm). Based on this experiment, the sensitivity of SPND used is 2.64 × 10-21 A/nv.cm. The thickness of Au and Cd are 0.04 mm and 1.00 mm, respectively. Then, the results were analyzed using the cadmium ratio (Fcd). The Fcd value for this research is 1.2 (15).

The SPND installation is shown in Figure 4, where SPND is inserted in the top grid plate of the Kartini reactor.

MCNPX is a software to generate transport code for neutrons, photons, and electrons. By using this software, the keff value is obtained, and keff is used to compute the effect of the material insertion on reactivity. The reactivity differences can be calculated based on equation 5 (16).

$$\Delta\rho = \rho' - \rho = \frac{k'-1}{k'} - \frac{k-1}{k} \quad (5)$$

where Δρ is reactivity differences, ρ is reactivity, and k is the effective multiplication factor. By considering a reactor at two different times so that ρ and k have two different values, ρ and ρ' also k and k'.

The neutronic analysis in this study was carried out by setting the Kartini reactor condition at 100 kW power. The control rod positions are at 100%, 70%, and 40% for the safety, compensation, and regulating rods, respectively. The fuel burn-up data used is the latest one in 2023. The Visual Editor (Vised) in this study is very helpful in determining the coordinates of the measurement location points carried out by SPND and gold foil (Au) activation to calculate the data.

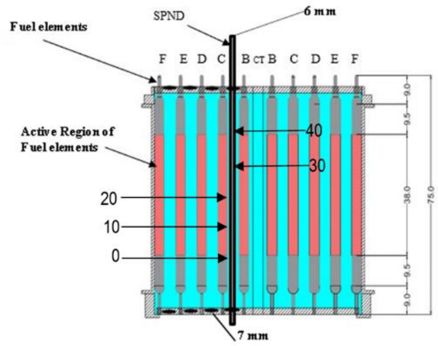

Figure 4. The SPND measurement.

RESULTS AND DISCUSSION

SPND data in the H16 location is shown in Table 2.

Table 2. SPND data in H16

Level (cm)	Neutron Energy Group 1 (× 10^{11} n/cm^{2}s)
0	0.756
10	1.040
20	1.130
30	1.040
40	0.725

Based on Figure 2, gold foils activation using a dummy fuel element that has a stick diameter of 6 mm and there are 4 sample placement points.

Position 1 – 3 placed bare gold foils, and position 4 placed gold foil covered by Cd. The masses of gold from positions 1 – 4 are 0.015 g, 0.014 g, 0.015 g, and 0.011 g, respectively. Activation was performed for 1 minute while the reactor was critical at 100 kW power. The neutron flux data by gold foil activation are shown in Table 3.

Table 3. Neutron flux by gold foils activation H16

Location	Energy		Total FLux
	Group 1 (× 10^{10} n/cm^{2}s)	Group 2 (× 10^{11} n/cm^{2}s)	(× 10^{11} n/cm^{2}s)
Position 1	3.40	1.70	2.04
Position 2	8.83	4.42	5.30
Position 3	12.40	6.20	7.44
Position 4	1.90	0.95	1.14

Based on the results in position 4, it is not possible to place a bare gold foil to obtain the total neutron flux because the dimensions of the stick to get into H16 are very close together so that, if there is an excess sample insertion it can cause the stick to get stuck. Energy range values that cannot be obtained experimentally can be resolved by calculations using the cadmium ratio (Fcd).

Self-shielding for the correction factor of the gold foil can be ignored because, based on the calculation results obtained, the magnitude of the self-shielding value is close to 0. The calculation of the self-shielding value can be shown in the equation 6.

$$G_{th} = \frac{1 - e^{-\xi}}{\xi} \quad (6)$$

where

$\xi = 2.V/S.\lambda^{-1} = t.\ \Sigma_a$ (17)

V is sample volume (cm^3), S is sample surface (cm^2), Σ_a is macroscopic absorption cross section (cm^2), t is foil thickness (cm) and λ is the absorption mean free path (cm).

After analyzing the placement of samples and SPND, a table related to the neutron flux measurements obtained can be made. There is a difference in levels because technically it was not possible to insert a camera as an observation tool inside the Kartini reactor core, given the very small diameter of the hole so that the camera cannot reach the measurement location. What was done at that time was only approaches to the measurement distance of the two measurement methods. A comparison of data obtained between SPND and gold foil activation data through Table 4 and the graph is shown in Figure 5.

Based on Table 4, it can be seen that only the 23 cm level has data between gold foil and SPND, this is because the aluminum stick for placing gold, which can be seen in Figure 2, has certain and limited dimensions. If the gold foils are placed in an inappropriate stick location, it can cause the sample to escape and fall into the reactor core. For SPND data, it cannot be at the 0 cm level because SPND is collided between the SPND support pipe and the grid plate above the reactor core so that it cannot go deeper. For levels 46 and 61 cm because, the placement requires a camera that is able to enter into the gridplate gap, which has a diameter of 7 mm while the facilities used do not have this equipment, so the method is done by taking a measurement approach

Table. 4 Comparison data of gold foils and SPND

Level (cm)	Gold Foils Data ($\times 10^{11}$ n/cm^2.s)	SPND Data ($\times 10^{11}$ n/cm^2.s)
0	1.14	-
3	-	4.54
13	-	6.24
23	7.44	6.81
33	-	6.24
43	-	4.35
46	5.30	-
61	2.04	-

Based on Figure 5, the graphical shapes of the two measurement methods have the same trend where the peak of the graph is at the centre. This indicates that the highest value is the midpoint of the active region of the reactor fuel. The difference between the highest flux value of SPND and gold foil is 8 %. Determination of neutron flux using the gold foil activation method has a higher level of accuracy, so in this study, it can be said that the SPND detector used is still in good condition and suitable for use.

On the other hand, neutron flux was also calculated and simulated using MCNPX software. Figures 6 and 7 show the simulation of neutron flux measurement points using the Visual Editor (Vised) software.

MCNPX simulation in this study uses 3000 cycles and burnup data in March 2023 for the calculation of neutron flux using tally F5. The result of neutron flux in MCNPX must be multiplied by the conversion factor to obtain the neutron flux value. The MCNP results can be normalized appropriately using the following conversion factor (18).

$$\left(\frac{1\,J/s}{W}\right)\left(\frac{1\,MeV}{1.602\times10^{13}\,J}\right)\left(\frac{1\,fission}{200\,MeV}\right) = 3.12\times10^{10}\left(\frac{fission}{W}.s\right) \quad (7)$$

For the Kartini reactor at a nominal power of 100 kW, the scaling factor is:

$$(0.1\text{ MW})\left(\frac{1\,neutron/cm^2}{source}\right)\left(\frac{2.4\,source}{fission}\right)\left(\frac{10^6\,W}{1\,MW}\right)\left(\frac{3.12\times10^{10}\,fission}{W.s}\right) = 7.49\times10^{15}\,n/cm^2s \quad (8)$$

After multiplying by the scale factor, the results of the neutron flux values are shown in Table 5.

Based on table 5 for each location, 5 times data collection was carried out starting from level 0 - 40 cm. Axial and radial location points can be seen in Figures 6 and 7. The data obtained using MCNPX software with tally program code F5.

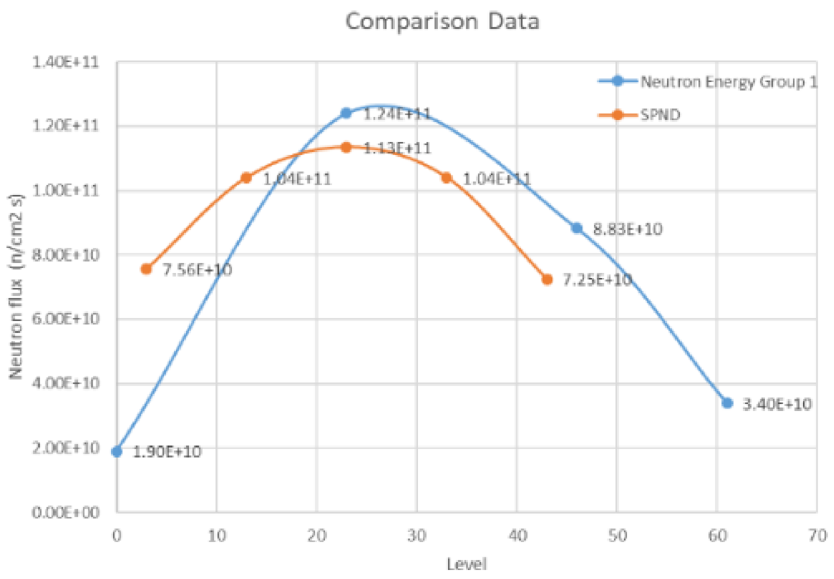

Figure 5. Comparison data of gold foils and SPND

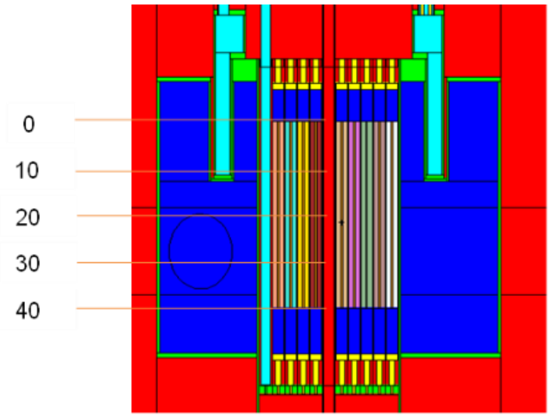

Figure 6. MCNPX model for Kartini reactor core (side view)

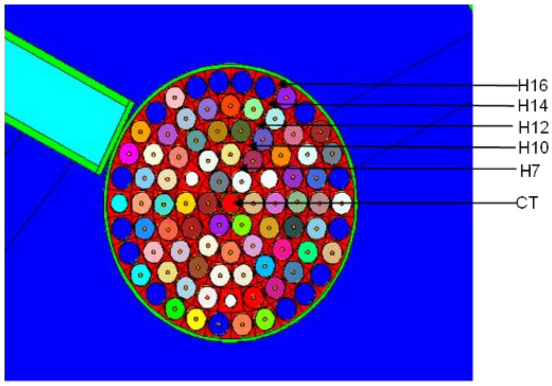

Figure 7. MCNPX model for Kartini reactor core (top view)

Table 5. MCNPX neutron flux data

Level (cm)	Location	Thermal Flux (× 10^{12} n/cm^{2}s)	Relative Error	Fast Flux (× 10^{12} n/cm^{2}s)	Relative Error	Total Flux (× 10^{12} n/cm^{2}s)
0	CT	1.83	0.0086	1.86	0.0069	3.70
10		3.42	0.0064	4.20	0.0047	7.62
20		3.84	0.0061	4.71	0.0044	8.55
30		2.71	0.0072	3.36	0.0052	6.07
40		1.14	0.0108	1.08	0.0093	2.23
0	H7	1.11	0.0099	1.91	0.0068	3.03
10		1.93	0.0079	4.33	0.0045	6.26
20		2.12	0.0076	4.81	0.0043	6.94
30		1.47	0.0092	3.33	0.0051	4.81
40		0.637	0.0123	1.00	0.009	1.64
0	H10	1.09	0.0105	1.74	0.0071	2.82
10		1.81	0.0084	3.86	0.0048	5.67
20		2.05	0.0079	4.28	0.0045	6.33
30		1.40	0.0096	2.99	0.0055	4.40
40		0.643	0.0131	0.92	0.0098	1.57
0	H12	0.888	0.0112	1.45	0.0078	2.34
10		1.47	0.0092	3.19	0.0052	4.67
20		1.66	0.0088	3.53	0.0051	5.19
30		1.16	0.0104	2.53	0.006	3.68
40		0.601	0.0132	0.76	0.0109	1.37
0	H14	0.873	0.0113	1.06	0.0093	1.93
10		1.34	0.0096	2.18	0.0064	3.52
20		1.43	0.0092	2.39	0.0061	3.82
30		1.07	0.0107	1.75	0.0071	2.81
40		0.606	0.0134	0.623	0.0121	1.23
0	H16	0.675	0.0113	0.715	0.0106	1.39
10		0.943	0.0098	1.34	0.0076	2.28
20		0.964	0.0097	1.45	0.0074	2.42
30		0.715	0.0111	1.08	0.0089	1.79
40		0.450	0.0135	0.434	0.0134	8.84

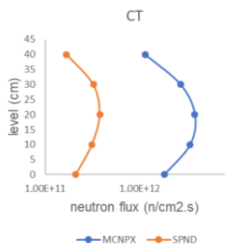

Figure 8. Axial in CT

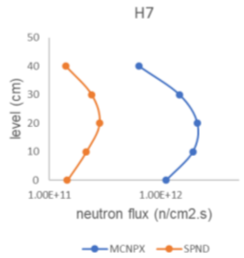

Figure 9. Axial in H7

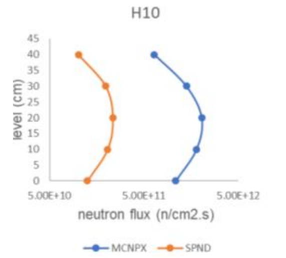

Figure 10. Axial in H10

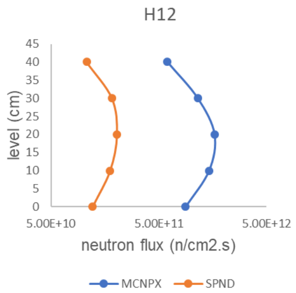

Figure 11. Axial in H12

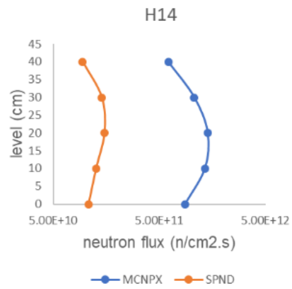

Figure 12. Axial in H14

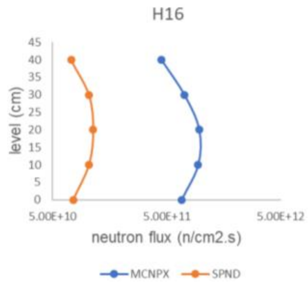

Figure 13. Axial in H16

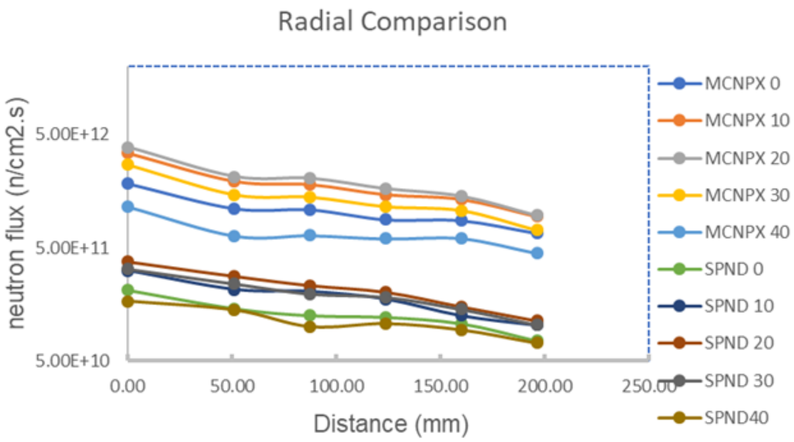

Figure 14. Radial data comparison SPND and MCNPX

Axial and radial data between MCNPX and SPND from location CT to H16 can be seen in Figure 8 - 14. Figures 8-14 illustrate the mapping of the magnitude of the neutron flux value inside the Kartini reactor core at a power of 100 kW. Figures are taken from the acquisition of calculations with MCNPX whose results are shown in Table 5.

Axially based on Figures 8-13, a sharp curve occurs in the middle area at each calculation location. This indicates that the location is the center location of the active material of the Kartini reactor fuel. Radially based on Figure 14, it would like to show that the largest neutron flux distribution is at the CT location or on the X axis of Figure 14 is 0.00 mm. The distance between CT and H16 is 196. 35 mm. While the distance between each hole location (CT, H7, H10, H12, H14 and H16) is 36.28 mm. There is still a difference in value when comparing SPND measurement and MCNPX results. MCNPX result is higher than the SPND measurement, but the trend shown in each graph is the same. This will be able to help in providing qualitative information that the active center region of the Kartini reactor fuel has a greater neutron flux. One of the causes of the difference is that the SPND detector has not been modeled in MCNPX. In terms of the shape of the flux distribution, the measurement and calculation results show good similarity.

CONCLUSION

Neutron flux measurements have been carried out using measurement methods with an SPND detector, gold foil activation, and calculation with MCNPX code. The SPND and gold foil activation data have almost the same neutron flux value; this is a reference that the SPND detector used is in good condition and valid for use. The considerable difference in data between SPND and MCNPX is due to the fact that the detectors used in MCNPX have not been modeled. However, in this study, calculation with MCNPX was used to predict the value of neutron flux in the Kartini core

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Department of Nuclear Engineering and Engineering Physics Universitas Gadjah Mada for the support to conduct this research and to the Directorate of Nuclear Facility Management (BRIN, Kartini reactor), Umar Sahiful Hidayat and Tri Nugroho Hadi Susanto as Kartini reactor operation management for providing the necessary equipment and assistance. This research was supported by the Ministry of Education, Culture, Research and Technology through "Penelitian Tesis Magister" scheme fiscal year 2023 with contract number 3236/UN1/DITLIT/Dit-Lit/PT.01.03/2023.

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