



Safety Analysis of Neutron Interaction with Material Practicum Module for the Kartini Internet Reactor Laboratory

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ABSTRACT

Kartini Research Reactor, which is situated in Yogyakarta, is a 100 kW TRIGA (Training, Research, and Isotope Production by General Atomic)-type reactor mainly used for educational and training purposes. A system for remote learning on nuclear reactor physics named the Internet Rector Laboratory has been developed and is fully operational since 2019. To enrich its curriculum, a new practicum module has been developed, that can be immediately implemented and does not require any additional equipment or materials. To ensure safety in reactor kinetics and radiation protection, a safety analysis on the implementation of the practicum module has been conducted using MCNP and ORIGEN utilizing the current conditions of the reactor regarding its fuel burnup and control rod positions at a certain power level. Based on the results of the analysis, the practicum is safe to perform from a neutronic and radiation protection perspective. Given the long half-life and the large amount of radiation exposure that comes from activation products of iron, it is recommended that only cadmium, boron, graphite, and aluminum are allowed to be irradiated during the practicum.

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1. INTRODUCTION

Kartini Research Reactor is a 100 kW TRIGA (Training, Research, and Isotope Production by General Atomic)-type reactor situated in Yogyakarta, mainly used for educational and training purposes [1–3]. To broaden its reach, a system for remote learning on nuclear reactor physics utilizing the internet and video conferencing has been developed and is fully operational since 2019. This System, called the Internet Reactor Laboratory (IRL Kartini), offers several practicum modules for universities and research institutes [4–7]. To enrich its curriculum, a new practicum module has been developed, that can be immediately implemented and does not

require any additional equipment or materials. The practicum module developed is on the Neutron Interaction with Materials. This practicum aims to show its participant the different interactions that different materials have on reactor power output and determine microscopic cross-section experimentally [8]. The materials proposed to be used in this practicum are boron, graphite, aluminum, iron, and cadmium to represent the different interactions of neutrons with materials. To ensure safety in reactor kinetics and radiation protection, a safety analysis on the Neutron Interaction with Material practicum module has been conducted. The results of the analysis will include the acceptability of the materials from a neutronic, amount of activation products generated, and the dose rate given.

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2. THEORY

The Internet Reactor Laboratory at the Kartini Reactor is a system where students can increase their comprehension of nuclear reactor physics that they receive in the classroom through practicums that are done remotely through the internet. The students will interact with the practicum instructor by teleconference throughout the practicum, see and take note of the phenomena that occurs via the website and is able to download the data for several parameters regarding the experiment by the end of the course. Currently, there are six available courses namely:

1. Introduction to Reactor Operations
2. Reactor Power Calibration
3. Temperature Coefficient of Fuel
4. Control Rod Reactivity Measurement
5. Reactor Criticality
6. Neutron Flux Measurement [6]

Neutron Activation occurs when neutrons induce radioactivity in materials. This process happens when neutron interacts with a material and is captured by the nuclei. Nuclei mass will be increased, which in turn caused instability within the nuclei and then it will enter an excited state [9]. The excited nuclei will decay by emitting gamma rays or particles or undergo electron capture or isomeric transition to achieve stability. The process of neutron capture by a material will result in the formation of activation products which are often radioactive [10].

As a means of radiation protection of nuclear workers, administrative limits of radiation exposure have been formulated. Usually, this process comes from scientific studies and reviews that have been discussed and deliberated by international organizations, which in turn publish international standards and derived as the national regulation in each country.

Per the regulations from the Nuclear Energy Regulatory Agency of Indonesia (BAPETEN), the effective dose limit for nuclear workers is set at 20 mSv each year [11]. The Center of Accelerator Science and Technology, which operates the Kartini Reactor, has set a dose constraint of 15 mSv per year for all workers at the site. Using the assumption of 2000 work hours each year, the dose constraint used is 7.5 μ Sv per hour [12].

The amount of activation product produced can be calculated from the weight of the radioisotope produced using the specific activity equation, as shown in equation (1).

$$SA = \lambda \times \frac{N_A}{A_w} \quad (1)$$

Where SA is the specific activity ($\frac{Bq}{gram}$), λ is the decay constant ($\frac{\ln 2}{t_{1/2}}$), N_A is the Avogadro number ($\frac{atom}{mol}$), dan A_w is the atomic weight ($\frac{gram}{mol}$). The amount of activation product produced is the radionuclide activity in becquerel multiplied by its respective specific activity [13].

3. METHODOLOGY

The Neutron Interaction with Martial Practicum is conducted using the following procedure:

1. The reactor is operated in critical condition at a low power level.
2. Using the pneumatic transfer system, the pneumatic operator inserts a single material sample.
3. After the sample enters the reactor core, the student observes the changes in the reactor power level.
4. The reactor operator returns the reactor power level to its initial power level. The student notes the changes in the position of the control rod.
5. The pneumatic system operator removes the sample from the reactor core; the reactor operator returns the reactor power to its initial level.
6. Stages 2 to 5 are repeated until all samples have been irradiated.

Therefore, in this study the safety analysis was conducted based on the procedure. In this study, to analyze the safety from the neutronic aspect, a study was carried out with Monte Carlo N-Particle Extended (MCNPX) code complemented with TRIGA MCNP and change2.exe. Radiation protection analysis and the resulting waste are calculated using ORIGEN 2.1 code. MCNPX is a general-purpose transport code for neutrons, photons, and electrons [3, 5, 14–16]. The value of k_{eff} is obtained using MCNPX, which is used to calculate the influence on the insertion of material on reactivity based on equation (2).

$$\Delta\rho = \rho' - \rho = \frac{k' - 1}{k'} - \frac{k - 1}{k} \quad (2)$$

ORIGEN is a computer code for simulations of nuclear fuel cycle and nuclide composition calculation. It can perform calculation on the buildup and decay of activation products [17–19]. Using ORIGEN, the radioactivity of the activation product is obtained and used to calculate the amount of activation product and its dose rate.

Neutronic analysis was carried out with the current conditions of the Kartini reactor as of the

second quarter of 2020. For instance, the positions and amount of U-235 fuel in each fuel element, control rods, and graphite. The position of the control rod in this study is in the 100%, 70%, and 40% position for the safety, compensation, and regulating rods, respectively.

Analysis of radioactive waste and radiation exposure was carried out by ORIGEN 2.1 with irradiation parameters carried out at a power level of 100 kW for two minutes. The cooling period is 0 seconds, 1 minute, 6 minutes, 10 minutes, 1 hour, 10 hours, 1 day, 6 days, 10 days, and 1 year. The calculation was conducted using photon library for activation products (library 101) and thermal 0.0253 eV cross-section library for activation products (library 201).

This study uses a conservative value where the irradiation is carried out at a power of 100 kW while the practicum is carried out at a lower power level.

4. RESULTS AND DISCUSSION

By using MCNP, calculations have been carried out with control rod position at the positions of 100%, 70%, and 40% for the safety, compensation, and regulating rod, respectively. This position is the position where the reactor operates critically at power levels between 10-100 kW [1]. One gram of material is placed in position F8, which is the position of the pneumatic irradiation facility in the Kartini reactor. This is done by replacing the pneumatic air voids with the material to be irradiated.

The calculation was done with the following parameters: 250 active cycles with the first 50 cycles ignored, an initial guess k_{eff} of 1.0, and a nominal source history amount of 14200 per k_{eff} cycle [1].

Using these parameters, calculations have been carried out on the effect of material insertion on k_{eff} . The initial k_{eff} value for the Kartini reactor without addition of materials is 1.00996 ± 0.00045 . It has been calculated the change in reactivity ($\Delta\rho$) as a result of adding the material using a pneumatic transfer system. The results of these calculations are shown in Table 1.

Table 1. Changes in reactor reactivity caused by material insertion calculated using MCNPX

No.	Material	K_{eff}	$\Delta\rho$
1.	Al	1.00965	-0.0003
2.	Fe	1.00876	-0.00118
3.	Cd	1.00706	-0.00285
4.	B	1.00532	-0.00457
5.	C	1.01106	0.001077

We can conclude that from all the materials tested, aluminum, boron, cadmium, and iron will induce negative reactivity, and thus will not cause a spike on the reactor power level. Carbon irradiation will cause a slight increase in reactivity but is still within the operational limits of the reactor. Caution is needed when removing the material so that the reactor protection system will not trigger scram.

Using ORIGEN, we can estimate the radioactivity of the generated activation products. The list of activation products is shown in Table 2.

Table 2. List of Activation Products calculated using ORIGEN [20]

Activation Product	Decay Mode	Half-life	Decay Product	Half-life
Activation Products from Boron Irradiation				
^{12}B	β^- (98.4%)	20.20 ms	^{12}C	Stable
	β^-, α (1.6%)		^8Be	8.19×10^{-17} seconds
Activation Products from Aluminum Irradiation				
^{28}Al	β^-	2.245 minutes	^{28}Si	Stable
Activation Products from Iron Irradiation				
^{55}Fe	Electron Capture	2.737 years	^{55}Mn	Stable
^{59}Fe	β^-	44.495 days	^{59}Co	Stable
Activation Products from Cadmium Irradiation				
$^{109\text{M}}\text{Ag}$	Isomeric Transition	39.6 seconds	^{109}Ag	Stable
^{107}Cd	β^+	6.50 hours	$^{107\text{M}}\text{Ag}$	44.3 seconds
^{109}Cd	Electron Capture	461.4 days	^{109}Ag	Stable
$^{111\text{M}}\text{Cd}$	Isomeric Transition	48.50 minutes	^{111}Cd	Stable
^{115}Cd	β^-	53.46 hours	$^{115\text{M}}\text{In}$	4.486 hours
$^{115\text{M}}\text{Cd}$	β^-	44.56 days	$^{115\text{M}}\text{In}$	4.486 hours
^{117}Cd	β^-	2.49 hours	$^{117\text{M}}\text{In}$	116.2 minutes
$^{117\text{M}}\text{Cd}$	β^-	3.36 hours	$^{117\text{M}}\text{In}$	116.2 minutes
^{117}In	β^-	43.2 minutes	^{117}Sn	Stable
$^{117\text{M}}\text{In}$	β^- (52.91%)	116.2 minutes	^{117}Sn	Stable
	Isomeric Transition (47.09%)		^{117}In	43.2 minutes

Based on the ORIGEN calculation, there are a few radioisotopes formed as activation products. Several of those products reach stability by undergoing chain decay.

All samples are inserted into the reactor core using the pneumatic transfer system and are irradiated separately. Immediately after irradiation, the samples are sent to a bin to decay. After one minute of cooling, all the boron-12 has decayed. After one hour, there are only trace amounts of aluminum radioactivity remaining. One hour after irradiation, 89.7% of the radioactivity inside the bin comes from the activation products of cadmium

irradiation, namely cadmium-107, cadmium-111m, cadmium-115, and cadmium-117. After one day of cooling, the main contributor of radioactivity inside the bin is cadmium-115 with 84.7% of the total radioactivity. After one year, there are only a few radioisotopes remaining. Iron-55 contributes to 89.2% of the total radioactivity inside the bin. Other remaining radionuclides are from cadmium activation products.

The amount of activation product produced per gram of each material irradiated is shown in Figure 1 to 4.

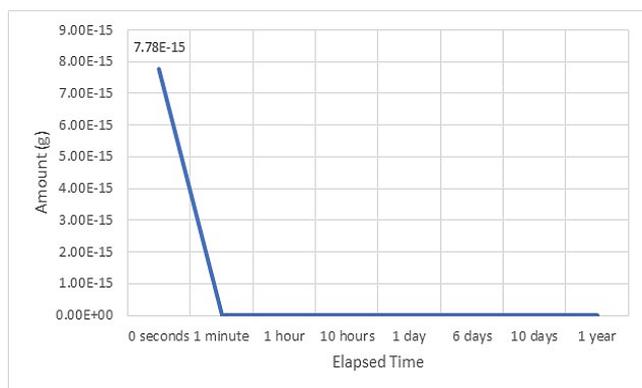


Fig 1. Amount of boron-12 produced from boron irradiation



Fig 2. Amount of aluminum-28 produced from aluminum irradiation

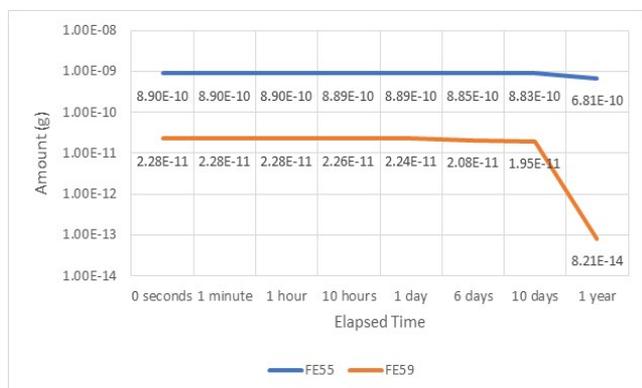


Fig 3. Amount of activation product produced from iron irradiation

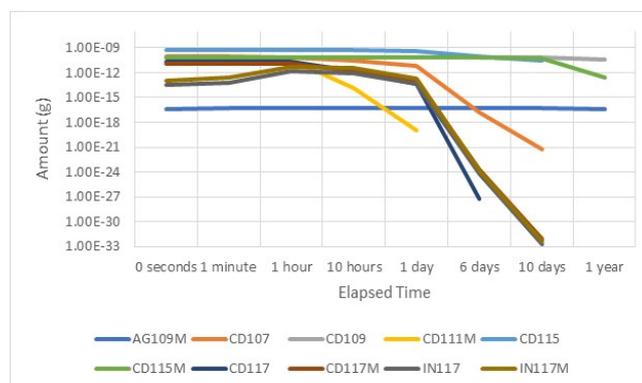


Fig 4. Amount of activation product produced from cadmium irradiation

To better understand the reduction in radioactivity caused by radioactive decay, a graph was made showing the radioactivity in Curie over several periods of cooling. Looking at figure 3,

special notice is given to the activation products of iron, due to its comparatively long half-life compared to other radioisotopes in the study. This is shown in figure 5.

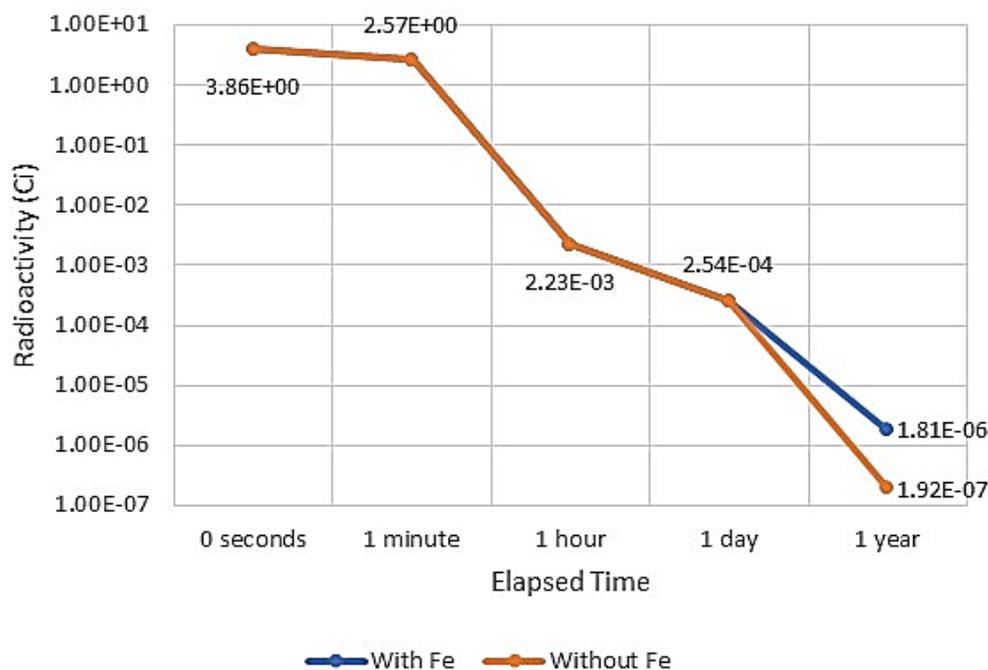


Fig 5. Radioactivity comparison with and without iron

Figure 5 shows the total radioactivity that resulted due to irradiation for each time the practicum is conducted, which is the total from each material. From Figure 5, we can see that due to the presence of iron, activation products after one year of cooling, the radioactivity is 9.43 times higher than those without iron.

Another reason is the impurities of iron increases the amount and variety of activation products. For example, when irradiating stainless steel 304 (SS-304), additional radioisotopes of magnesium-27, manganese-56, nickel-59, nickel-63, and nickel-65 are also inadvertently produced during the irradiation process. Meanwhile, irradiation of aluminum alloy 1050 generates negligible amount of activation products due to its high purity.

Using the radioactivity, we can calculate the radiation dose rate that may be received by the personnel. The estimation of the dose rate given per gram of material irradiated shown in table 3.

Table 3. Dose Rate Estimate

Element	Dose Rate in mSv/h		
	0 Seconds	1 Minute	1 Hour
Aluminum	30.82	22.62	2.66×10^{-7}
Iron	7.51×10^{-6}	7.51×10^{-6}	7.50×10^{-6}
Cadmium	1.20×10^{-2}	1.19×10^{-2}	6.76×10^{-3}
Total	30.83	22.63	6.77×10^{-3}

Due to high dose rate that can be received by the pneumatic transfer system operator due to exposure from aluminum-28 radioactivity, special

care must be given so that the operator will not become exposed to radioactivity for too long. The pneumatic transfer system at the Kartini reactor has a bin to receive irradiated material located on a different floor. Still, it must pass through the pneumatic transfer system room. Therefore, the operator must immediately send the irradiated aluminum pneumatically to the bin as soon as it exits the reactor core.

5. CONCLUSION

From the results, it can be concluded that the practicum is safe to perform from a neutronic and radiation protection point of view.

Given the long half-life and the large amount of radiation exposure that comes from activation products of iron, it is recommended that only cadmium, boron, graphite, and aluminum are allowed be irradiated. The usage of cadmium can also be reconsidered as boron can provide similar results with less radioactive waste and exposure. By using only boron, graphite, and aluminum, all activation products will decay within 6 hours.

To protect pneumatic operators from radiation exposure, especially from aluminum activation, lead shielding may be added to the pneumatic counting device and establish a perimeter around the bin out during the practicum.

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AUTHOR CONTRIBUTION

Prasetyo Haryo Sadewo and Puradwi Ismu wahyono has contributed equally as the main contributors to this paper. All authors have read and approved the final version of the paper.

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