Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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To cite this article: S Syarip and P I Wahyono 2019 *J. Phys.: Conf. Ser.* **1157** 032002

Experience in nuclear reactor physics laboratory exercises using Kartini research reactor

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Abstract. The experience in using Kartini nuclear research reactor for reactor physics laboratory exercises is presented. The aim of this paper is to discuss the effectiveness of nuclear reactor physics laboratory exercises using Kartini reactor. The method used is through a comparative reference study with the similar activities at other institutions. Software packages and procedural guides have been developed and used for reactor power and control rod worth calibrations, criticality experiment, experiments to study the xenon stability, neutron flux measurement, reactor start-up/ shutdown operations, etc. For illustration, a computer simulation for reactor criticality experiment is described and result from practical experiment is presented. In conclusion, it has been demonstrated that the implementation of reactor physics laboratory exercises using Kartini reactor has a good performance and it was an important role in developing human resources in nuclear reactor field for the country. It is hoped that in the future, Kartini reactor will contribute to regional nuclear education and training programs.

1. Introduction

Kartini research reactor has been used by several universities surrounding Yogyakarta for training and education in nuclear reactor engineering field. The reactor is very suitable for education and training programs in the field of nuclear reactor, particularly for the basics understanding in reactor physics & kinetics, reactor operations phenomena, reactor instrumentation & control system, as well as reactor utilization for elementals analysis [1]. The paper is intended to give an overview on the effectiveness of the practical implementation of the reactor physics laboratory exercises that have been implemented so far. It is hoped therefore, it can be used as a feedback for the improvements.

The users of Kartini reactor for reactor physics laboratory exercises are included students of Department of Physics and Faculty of Engineering University of Gadjah Mada Yogyakarta, Polytechnic Institute of Nuclear Technology (POINT-BATAN) Yogyakarta, Department of Physics Faculty of Science & Mathematics Diponegoro University, Department of Physics Faculty of Science & Mathematics State University of Jenderal Soedirman (UNSOED) Purwokerto, Department of Physics Faculty of Science & Mathematics State University Sebelas Maret (UNS) Solo, S2 (Master Science) Program Department of Mechanical Engineering Bandung Institute of Technology (ITB), etc.

Practical implementation is designed to deliver the student to understand in more detail the physical phenomena occurring in the nuclear reactor, and the student is able to perform the measurement and analysis of reactor physics parameters. Therefore, the reactor physics laboratory manual should contain enough topics comprehensively which covers reactor physics, kinetics and control, and operation of nuclear reactor parameters. The materials of reactor physics laboratory exercises are compared with with the similar activities at reference institutions. For an illustration, a computer simulation for reactor criticality is described and results from practical experiments are presented. Description and analysis of reactor physics practical implementation is expected to be a feedback to enhance reactor physics laboratory services and improvement in laboratory manual using Kartini reactor in the future to contribute to nuclear power plant (NPP) personnel development.

2. Description of Kartini research reactor

Kartini research reactor is one of the three research reactors operated in Indonesia, located at the Centre for Accelerator Science and Technology (CAST). CAST was founded in 1964 as one of the research facilities under the authority of the National Nuclear Energy Agency (BATAN). Kartini reactor has been operated since 1979 and the latest operation license from Regulatory Body (BAPETEN) valid until 2019. Kartini reactor is a TRIGA Mark-II reactor whose current utilization is being developed as a basic nuclear reactor training and part of the nuclear training centre (NTC) [2].

NTC is a training program in the field of nuclear and applied physics particular in reactors utilization, for educational institutions and research personnel in the research activities in the field of ionizing radiation and reactor technology. The training that offered by NTC can be either reactor criticality experiment, power reactors calibration, control rods calibration, measurement of reactivity and so forth. The training was conducted by using data taken directly from the reactor operation. The other facility in the NTC is the NPP functional simulator of high temperature gas reactor (HTGR) type [3].

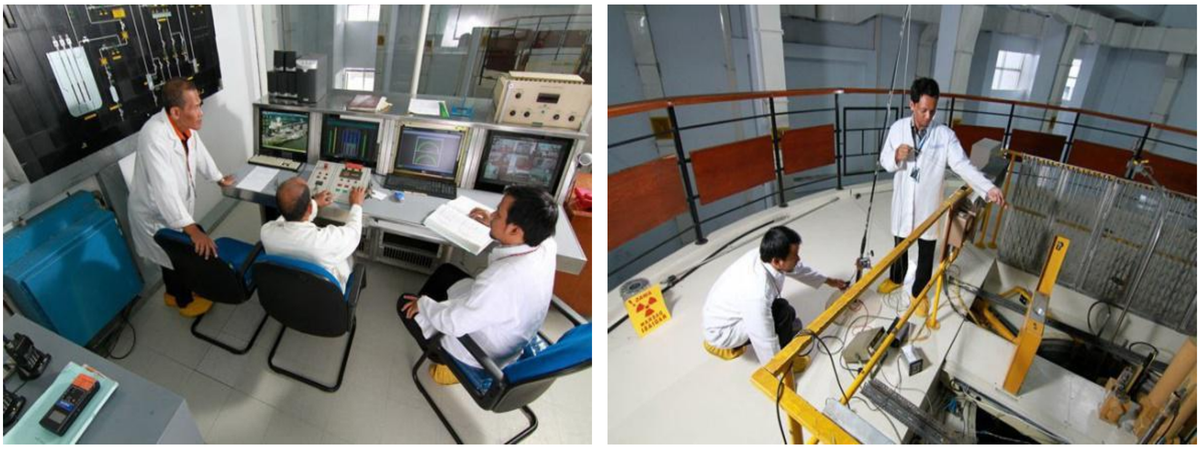

Figure 1. View at control room and Kartini reactor deck.

2.1. Kartini reactor core

The Kartini reactor core is a configuration of reactor fuels and control rods, surrounded by neutron reflector made of graphite. The reactor core consists of 90 holes forms the ring which can be filled with reactor fuels and control rods. The Kartini reactor uses standard TRIGA fuel, type 104 and type 204 made by General Atomic. The standard fuel of 104 type has 8.5% -9% uranium content with ^{235}U enrichment 19.75% using zirconium hydride mixture (UZrH) with H/Zr ratio = 1.7. The ^{235}U content in each fuel varies from 37 grams up to 39 grams and in average the weight of ^{235}U in each fuel element is 38 grams. Whiles the fuel type 204 is an instrumented fuel element i.e. a standard fuel provided with thermocouple for fuel temperature monitoring. In addition the Kartini reactor has a dummy fuel element containing graphite located in the outer ring of the reactor core.

The configuration of Kartini's reactor fuel in May 2016 are 67 fuel elements of type 104 and 2 fuel elements of type 204 distributed in the reactor core, 2 control rods in C ring and a control rod in E ring. Empty fuel column filler is given 15 dummy elements. The standard Kartini reactor fuel and core configuration is described in Figure 2.

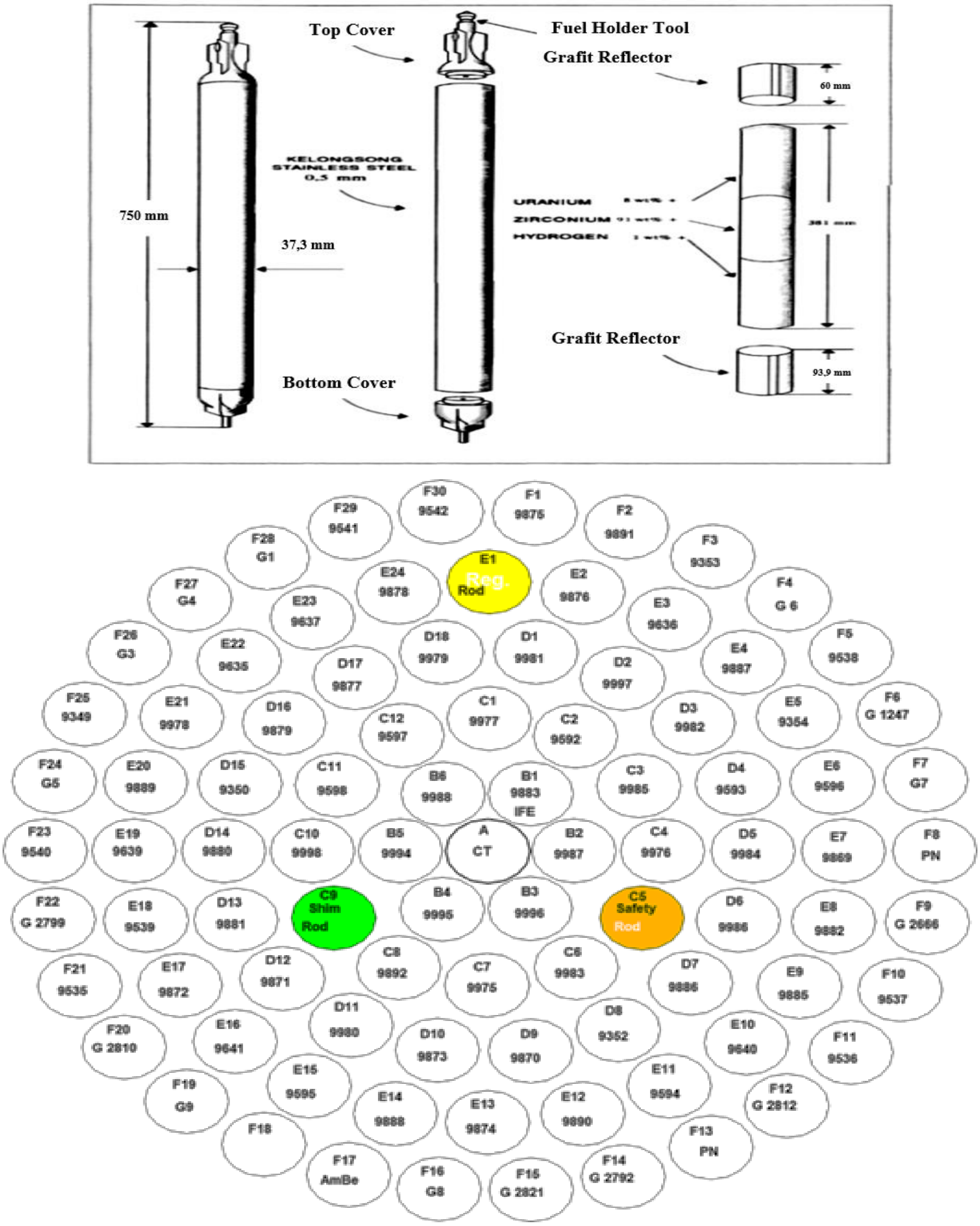

Figure 2. Kartini reactor fuel and core configuration.

2.2. TRIGA MCNP computer code

One of the functional simulator used for reactor physics laboratory exercises is TRIGA-MCNP, i.e. a computer code for critical mass calculation of TRIGA Mark-II reactor type (Training, Research and Isotope production by General Atomic), developed by Putranto Ilham Yazid [4]. The critical reactor condition is a state where the rate of neutron population in the reactor core is constant. Each nuclear reactor requires a certain fuel mass to reach a critical condition, the mass is called critical mass. The reactor criticality experiment is one of the training topics on the NTC.

TRIGA-MCNP is a versatile tool program for criticality calculation of TRIGA Mark II reactors by using MCNP code. It will generate an MCNP input file that can be used directly for solving KCODE problem. The fission source is modelled with standard KSRC card, along with a table of fission neutron source points. These points are generated uniformly inside fuel elements in the core, including fuel follower control rods. No lattice nor repeating cell is used in modelling the problem's geometry, so that users could easily modify the file.

The geometry of TRIGA Mark II reactor is described as a 3-dimensional full scale and detail model, which includes: reactor core, graphite reflector, piercing and radial hollows, rotary specimen rack, beam-ports, thermal- and thermalizing columns, reactor tank and cooling water, biological shielding, and bulk shielding tank. Almost all components are modelled in detail in which dimensions and materials are taken from the original technical drawings of General Atomics-USA and other sources. Users may arbitrarily put the following items in the core for example: U85, U12 and U20, that is 8.5, 12 and 20 w-% of 20 % ^{235}U enrichment of standard TRIGA fuel elements, respectively.

3. Material and methods

The method used to analyse the effectiveness and material completeness of education and training programs is to review the material as well as the implementation of education and training programs mainly reactor physics laboratory exercises and compared them with the similar activities at other institutions. As references for comparison among others: TRIGA Reactor Vienna, VR-1 Reactor at Czech TU-Prague, and VTT reactor at Helsinki University of Technology [5,6,7]. The materials for laboratory exercises is mainly compared to the materials contained in IAEA-TCS-57 [8].

Furthermore, to give an illustration of laboratory exercise, a computer simulation for reactor criticality is described and results from practical experiments are presented. A reactor core configuration and criticality calculation (simulation) is done by using TRIGA-MCNP, then the result is compared with the criticality experiment result. In the initial reactor start-up, it is very important that the approach to criticality be performed very slowly and carefully, as the actual mass, or number of fuel elements required for criticality is unknown. For this purpose, the sub-critical multiplication relationship is used i.e.:

$$M = \frac{1}{1-k} \tag{1}$$

Where M is a sub-critical multiplication, and k is neutron multiplication factor. By placing a number of additional sensitive neutron detectors around the core, such that the detectors are measuring source neutrons multiplied by the sub-critical fissions in the core, a measure of the multiplication can be obtained from the following relationship:

$$M = A\,x\,\frac{count\ rate\ after\ loading\ fuel\ (\sim source\ fissions\ )}{initial\ count\ rate\ (\sim source\ only)} = A\,x \frac{R}{S} \tag{2}$$

A is a constant which is dependent on detector efficiency, etc. R is count rate after fuel loading and S is count rate of neutron source. The approach to criticality then consists of loading fuel elements in steps, measuring the count rates on the detectors after each step and plotting 1/M as a function of the fuel mass or number of elements. As an indicator for criticality can be seen if k approaches unity then 1/M or S/R approaches zero.

4. Results and discussion

4.1. Education and training material analysis result

The recent reactor physics laboratory exercise material conducted using Kartini reactor consists of 8 topics [3], and this is assumed has met the requirements for understanding the basics of reactor physics in general [9]. The topics is listed in Table 1, then it is compared with the materials/topics of reactor physics laboratory at several universities/ institutions such as: Atominstitute, Vienna [5], Czech Technical University [6], and Helsinki University of Technology [7], as well as practical reactor physics organized by the IAEA [8]. The material and the type of practical reactor exercise at the Czech Technical University, and Helsinki University of Technology, is about the same as presented in Table 2, whereas the material in Atominstitute and the IAEA is more complete and comprehensive as can be seen in Table 3.

Based on Table 1, 2, and 3 can be seen that the material for the reactor physics laboratory exercises using Kartini reactor was complete enough, almost the same as the material in the Czech Technical University, and at the Helsinki University of Technology. But when it compared with the laboratory exercise materials held in Atominstitute (IAEA), still needs a little improvement. It is important to note that the need for improvement and additional variation in topics of practical reactor exercises are very important, as basic steps of scientific method to investigate phenomena, acquire new knowledge and correct previous knowledge. The scientific method guides the dynamical relationship between theory and experiment: theory is modified based on new experimental data and it can be used to guide future measurements [10].

Table 1. Material of reactor physics laboratory exercise at Kartini reactor [1]

No	Topics
1	Introduction to reactor operation
2	Reactor criticality experiment
3	Control rod calibration
4	Reactor power calibration
5	Measurement of neutron flux & spectrum
6	Measurement of fuel temperature & reactivity coefficient
7	Measurement of delay neutron fraction
8	Measurement of fuel burnup using gamma scanning method

Table 2. Material of reactor physics laboratory exercise at *Czech TU and Helsinki UT* [6,7]

No	Topics
1	Reactor start-up – approach to criticality
2	Control rod calibration
3	The effect of temperature on reactivity
4	Determination of delayed neutron precursor groups
5	Digital control and safety systems of the VR-1 reactor
6	Neutron activation techniques
7	Study of the reactor dynamics

Table 3. Material of reactor physics laboratory exercise at *Atominstitute* Vienna and IAEA [5,8].

No	Topics	No	Topics
1	Measurement of the thermal neutron flux density	8	Control rod calibration and determination of excess reactivity in the core
2	Measurement of the fast neutron flux density in the core centre	9	Calibration of the shim rod in the sub-critical region
3	Determination of the material and void feedback on reactivity	10	Reactivity values of fuel elements in various core positions
4	Measurement of the absorption cross-section	11	Reactor power calibration and temperature coefficient of the reactivity
5	Determination of the reactivity and the reactor period	12	Demonstration of a reactor pulse with different reactivity insertion
6	Measurement of the background radiation around the operating reactor	13	Gamma spectroscopy of TRIGA fuel
7	Reactor criticality experiment		

4.2. A case study on reactor criticality simulation and experimental results

Several computer software for educational facility on reactor physics experiment of Kartini Reactor have been developed and used such as CPEM (core parameter evaluating module) intended for facilitating the evaluation of experimental data of several Kartini reactor parameters such as control rod worth, reactor power, and absolute neutron flux determinations and TRIGA MCNP have been developed [4,11]. TRIGA-MCNP computer code used for reactor criticality analysis. Prediction of the accurate minimum critical mass is very important for fuel loading of reactor core in such that a suitable core excess can be achieved to maintain reactor operation in continuous long term services. The criticality calculation using TRIGA-MCNP is done to determine the fuel configuration in the reactor core in such that the minimum critical mass was achieved. Based on the calculation can be found the effective multiplication factor (kef) and the amount of fuel needed for the reactor to reach a critical condition.

The critical simulation results using TRIGA-MCNP is shown in Table 4 and the experimental result is shown in Table 5 and Figure 3. The experimental steps as mentioned earlier and based on equation (1) and equation (2). The approach to criticality then consists of loading fuel elements in steps, measuring the count rates on the detectors after each step and plotting 1/M as a function of the fuel mass or number of elements. As an indicator for criticality can be seen if k approaches unity then 1/M or S/R approaches zero, this phenomena is described in Figure 3.

Table 4. Multiplication factor (k) and critical mass calculated by TRIGA-MCNP

Loading	No. of fuel	^{235}U (g)	k
-	61	2318	0,97128
D4	62	2356	0,97976
D8	63	2394	0,98587
D13	64	2432	0,99359
D17	65	2470	1,00076

Table 5. Experimental result of critical mass (counting rate vs fuel loading)

Loading	No. of fuel	^{235}U (g)	Count rate (cps)	1/C
D4	62	2334,31	31,63333	0,031612
D8	63	2372,38	70,62778	0,014159
D13	64	2410,34	97,63333	0,010242
D17	65	2448,13	168,2722	0,005943
E11	66	2486,17	580,4611	0,001723
E25	67	2596,96	553937,8	1,8.E-06

The extrapolation method is divided into three steps as illustrated in Figure 3. The blue line is the first extrapolation (Step-1) with two initial experimental data points that yield the first critical mass estimate of 2400 grams. Step-2 is illustrated by red lines derived from extrapolated third and fourth data to obtain a second critical mass estimate of 2450 g, while the green line shows the third step (Step-3) from the fifth and sixth data resulting in the third critical mass estimation of 2500 g. From these three extrapolation steps we can create a new line with a trend-line polynomial approach (black dote line) as the basis for determining the minimum critical mass of the reactor. When compared between all curves or lines, the estimated phase one obtained gives a critical mass amount of 2400 gram which is too small. So the second step is extrapolated, where at this step the condition of the reactor is still not critical. In the extrapolation of step three, the reactor has undergone a critical state resulting in an estimated mass of ^{235}U of 2500 g.

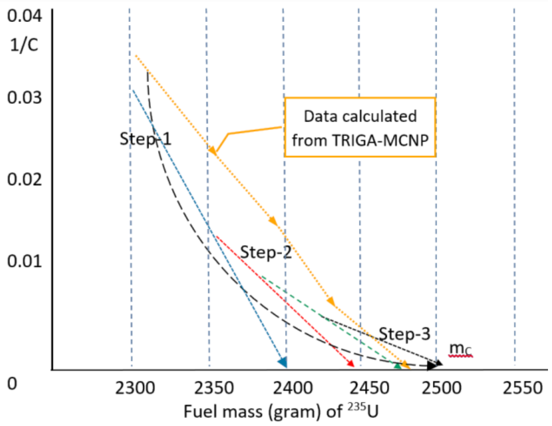

Figure 3. Reciprocal counting rate (1/C) versus fuel loading.

The results of TRIGA-MCNP calculations shows that Kartini reactor core will be critical with core configurations contain 65 fuel elements, which is equivalent to a critical mass of 2470 grams. The Kartini reactor criticality experiment result showed that the minimum critical mass measured is 2500 g of ^{235}U with the number of fuel elements 65. The Kartini reactor core was then loaded by 69 fuel elements to increase the core excess. The result shows that criticality simulation using TRIGA-MCNP and criticality experimental results gives a good agreement with 1.5 % error. It is showed that TRIGA-MCNP code can be used to predict the minimum critical mass of Kartini reactor with good accuracy. By using the computer TRIGA-MCNP computer software can assist an instructor in his/her classroom to carry out his/her challenge to teach, and this case is in accordance with reference [12,13].

5. Conclusion

The reactor physics laboratory exercises program at Kartini research reactor has been implemented in a good manner, although this is still a need to increase the quality of service in order to serve more comprehensive both technically and materially. For more comprehensive services in order to contribute to regional nuclear education and training programs in the future, the improvement on the laboratory exercises arrangement is a necessity. A case study on reactor criticality simulation using TRIGA-MCNP and experimental results give a good agreement with 1.5% error. It is hoped that in the future, Kartini reactor will contribute to regional nuclear education and training programs.

Acknowledgments

The authors would like to thank the Director of Centre for Accelerator Science and Technology Yogyakarta, as well as to the Head of Reactor Division and all staffs for their support

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