UDC 621.039.51

USE OF THE MONTE CARLO SERPENT CODE FOR MODELING THE SECOND SERIES OF EXPERIMENTAL DATA OF KUCA SUBCRITICAL INSTALLATION

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Modeling of the neutron-physical characteristics of the Kyoto University KUCA subcritical facility was conducted using the Monte Carlo Serpent code. The effective multiplication factors for the critical experiments of the series II on the KUCA research subcritical facility were calculated. The presented calculation results were compared with the experimental results and the results of the calculations made using the Monte Carlo codes MCNP6 and KENO-VI.

INTRODUCTION

Active research of accelerator-driven subcritical systems began in the early years of two thousand. For example, IAEA began the work on a research project called "Analytical and Experimental Benchmark Analyzes of Accelerator-Driven Systems" [1]. The overall project objective was to expand the possibilities for developing and using advanced reactor technologies in the field of subcritical systems [1]. Within the framework of the project modeling and experiments were performed on the demonstration subcritical systems controlled by an external source of neutrons, for example, YALINA (Belarus) [2], KUCA (Japan) [3, 4]. Since then, active research in the development of ADS, as well as validation of computational methods and procedures that can be used for it has been conducted worldwide [1].

The aim of the present paper is to validate the new Monte Carlo Serpent code for modeling advanced nuclear subcritical systems controlled by an external neutron source, namely the study of the applicability of the Serpent calculation code [5, 6] for modeling the subcritical system of KUCA Kyoto University Research Reactor Institute; the experiments with that subcritical system were held in December 2012 [3] and January 2015 [4].

Validation itself consists in a comparative analysis of the calculation results obtained using Serpent, the experimental results of the KUCA series II, and the results obtained in the atomic center of Bariloche, Argentina [7] with the use of the MCNP-6 [8] and KENO-VI [9] calculation codes.

The present article briefly describes the configurations of the second series of experiments on the KUCA Kyoto University subcritical system (December 2012) [3], and also presents the results of the effective multiplication coefficients calculations made using Monte Carlo Serpent code version 2.1.26. A library of evaluated nuclear data ENDF-B-VII.0 [10] was used.

1. SERPENT CALCULATION CODE

Serpent is a multipurpose Monte Carlo code that was developed at the VTT Technical Research Center in Finland [5]. The development of Serpent code began in 2004, and at the moment the first version of the code is distributed free of charge through the OECD/NEA and RSICC databank since 2009. This code is successfully used for modeling various types of advanced reactor systems [11, 12].

In Serpent there is the option to model subcritical systems controlled by an external source of neutrons. This is the reason for its use in the framework of the FP7 EUROATOM FREYA project, led by the Belgian Nuclear Research Center (SCK CEN) and carried out from 2011 to 2016. A series of experiments were conducted at the VENUS-F installation. At the same time, one of the main goals of FREYA was to research and verify methods for reactivity monitoring [2]. Therefore, when developing the FREYA project in SCK CEN, the calculation codes MCNP5 and Serpent2 were simultaneously used to compare the calculated results with experimental data, as well as to study the applicability of Serpent for VENUS-F modeling [13].

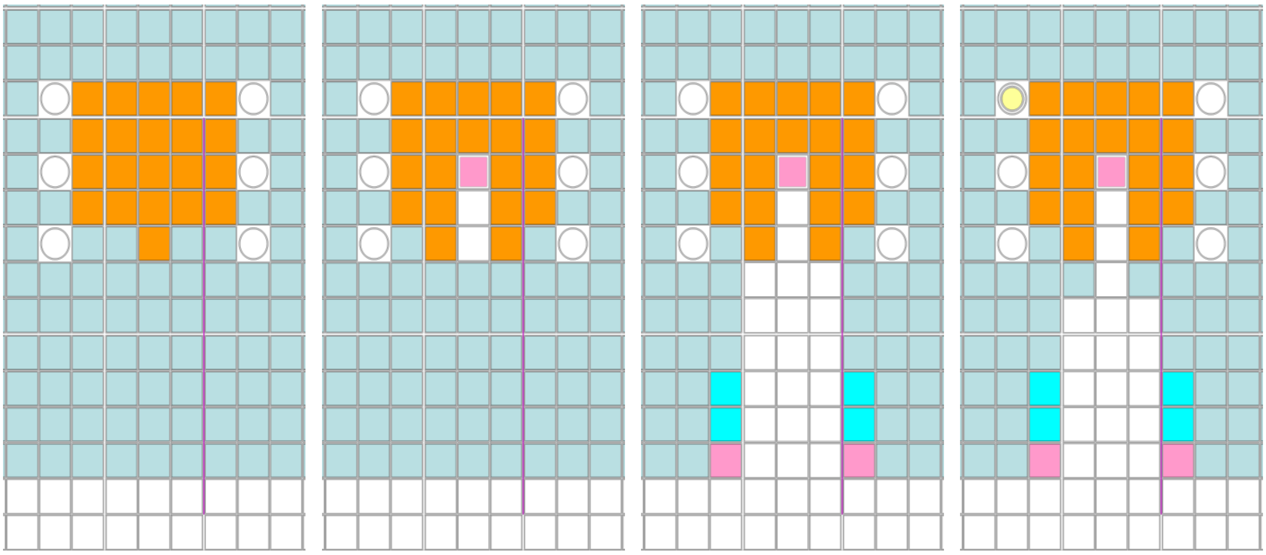
2. DESCRIPTION OF KUCA SUBCRITICAL SYSTEM

Experiments of phase 1, series II, configuration cases from II-1 to II-4 were chosen from [3] for modeling and calculation analysis. Phase 1 consisted in the research of the multiplying properties of a subcritical system without the operation of an external neutron source, depending on the depth of the absorbing control rods.

Each core configuration of KUCA subcritical system has a specific set of cells: fuel assemblies, reflector, shielding elements. In addition, there are other components such as control/protective rods, detectors. The cell itself is a 152.4 cm high structure, which has a square cross-section and consists of blocks of various materials in the form of rectangular parallelepipeds.

Fuel plates consist of uranium-aluminum alloy (U-Al) enriched with uranium-235 at 93%.

Fig. 1 shows the Serpent-visualization of the calculated models of the considered configurations from II-1 to II-4 (top view in cross-section *Z* = 73.5 cm, side view in cross-section *X* = 63.995 cm).

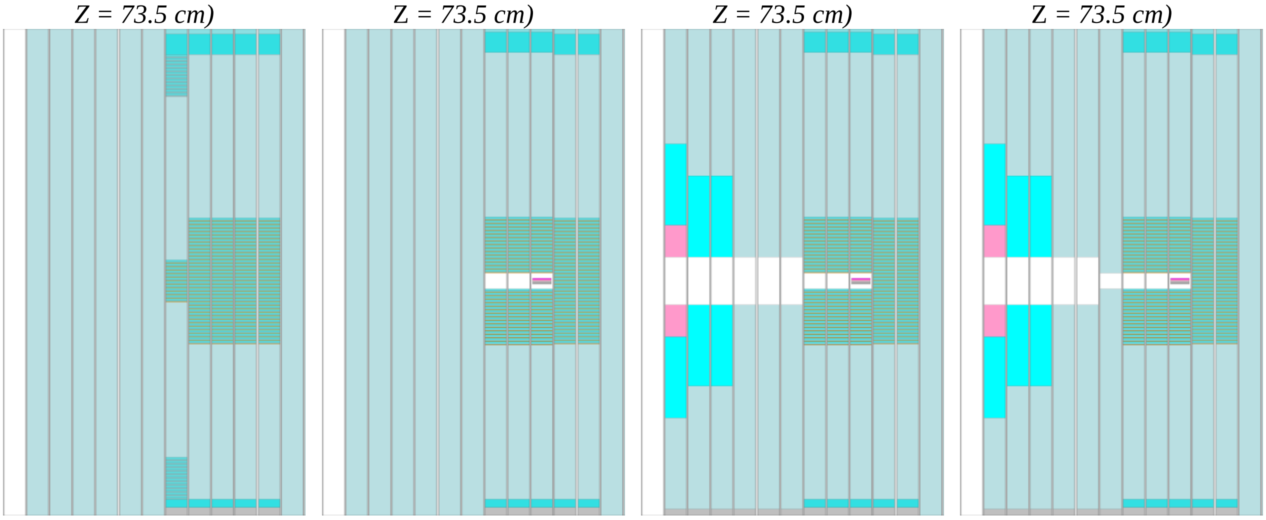


KUCA configuration II-1 (top view in cross-section *Z = 73.5 cm)*

KUCA configuration II-2 (top view in cross-section *Z = 73.5 cm)*

KUCA configuration II-3 (top view in cross-section *Z = 73.5 cm)*

KUCA configuration II-4 (top view in cross-section *Z = 73.5 cm)*



KUCA configuration II-1 (side view in cross-section *X = 63.995 cm)*

KUCA configuration II-2 (side view in cross-section *X = 63.995 cm)*

KUCA configuration II-3 (side view in cross-section *X = 63.995 cm)*

KUCA configuration II-4 (side view in cross-section *X = 63.995 cm)*

Fig. 1. Serpent-visualization of the geometric structure of the calculation models KUCA II-1–II-4 configurations

To measure the reaction distribution rate in the central region of the subcritical system, an indic wire with a diameter of 1.5 mm and a length of about 60 cm has been placed [3]. The fission chambers (FC1-3) and the detectors UIC (UIC4, UIC5) specified in [3] have been replaced by cells with airspace. The source of neutrons (*N*) has also been replaced by a polyethylene block (data on the structure and material composition of these components are not provided in the source [3]).

The material composition, as well as a detailed description of the geometry of the core considered configurations of subcritical system, which have been used in the modeling of cases from II-1 to II-4, are given in the source [3] and will not be mentioned in this work again.

3. CRITICAL, SUBCRITICAL AND SUPERCRITICAL STATES MODELING OF THE SECOND SERIES OF KUCA EXPERIMENTS

When KUCA subcritical system was tested, the regulating of the subcriticality level was performed by maintaining the control/absorber rods at a certain height relative to the base of the subcritical system, according to [3].

When KUCA was tested, the subcritical state was provided by full immersion of the control rods C1

(No 151), C2 (No 152), C3 (No 153). It is important to note that all protective rods S4 (No 154), S5 (No 155), S6 (No 156) were completely removed from the core of the subcritical system.

In Table 1, positions (in Z from bottom to top) of bottom of control absorber of control rods in different configurations are given.

The critical state for each experiment was provided by maintaining one control rod at a certain height above the base of the subcritical system.

As shown in [3], the supercritical state was "predicted by the inverse period method based on calibration curves" with full lifting of the control and protective rods from the core of the subcritical system.

The description of the geometrical characteristics of the control/protective rods is presented in the source [3].

Table 1

Lift height of the absorber rods relative to the lower boundary of the subcritical system for various KUCA configurations, cm [3]

Designation according to [3]	C1	C2	C3	S4	S5	S6
KUCA configuration	Rods lift height relative to the lower boundary of the subcritical system, cm					
II-1	131.4	131.4	63.594	131.4	131.4	131.4
II-2	63.748	131.4	131.4	131.4	131.4	131.4
II-3	131.4	131.4	74.248	131.4	131.4	131.4
II-4	131.4	131.4	55.324	131.4	131.4	131.4

4. RESULTS OF SERPENT MODELING AND ANALYSIS OF THE RECEIVED DATA

The experimental data of the effective multiplication factors and data calculated using Serpent is presented in Tables 2 and 3.

The results presented in [3] were converted from reactivity units to effective multiplication factors according to the following formula:

$$\rho = \frac{K_{\text{eff}} - 1}{K_{\text{eff}}}. \tag{1}$$

Table 2

Results of the effective multiplication factors numerical analysis of the series II KUCA experiments

Experiment (configuration)	Source of results	Subcritical state (s.s.)	Critical state (c.s.)	Supercritical state (sup.s.)
		K_{eff}	K_{eff}	K_{eff}
II-1	EXP	0.99213	1.00000	1.00143
	Serpent	1.00028	1.00778	1.00944
II-2	EXP	0.99328	1.00000	1.00247
	Serpent	1.00059	1.00718	1.01039
II-3	EXP	0.99115	1.00000	1.00037
	Serpent	0.99619	1.00514	1.00569
II-4	EXP	0.99303	1.00000	1.00233
	Serpent	1.00165	1.00798	1.01012

Table 3

Difference between the values of the effective multiplication factor of series II

Experiment (configuration)	Difference in results	Subcritical state (s.s.)	Critical state (c.s.)	Supercritical state (sup.s.)
		K_{eff}	K_{eff}	K_{eff}
II-1	EXP-Se	-0.00815	-0.00778	-0.00801
II-2	EXP-Se	-0.00731	-0.00718	-0.00792
II-3	EXP-Se	-0.00504	-0.00514	-0.00532
II-4	EXP-Se	-0.00862	-0.00798	-0.00779

Note (to Tables 2, 3): EXP – experimental results, according to [3]; Serpent – results obtained using the Serpent calculation code in the course of performing the present work; (EXP-Se) – difference between the experimental results and the results obtained using the Serpent calculation code.

A numerical analysis of KUCA experimental data [3] was performed using the Monte Carlo Serpent code and the ENDF/B-VII.0 Evaluated Nuclear Data Library, which was included in the Serpent package. The HCH2.71t library of thermal neutron scattering was used [14] for accounting the thermal neutron scattering in polyethylene. It should be noted that the majority of Ukrainian organizations do not have access to modern libraries of estimated nuclear data, therefore, an older version of the library of thermal neutron scattering in polyethylene was used in the presented calculations.

Serpent was used for all calculations of the effective multiplication factor. The "set pop 10000 1000 100" option, where "10000" is the number of neutrons per cycle, "1000" is the number of active cycles launched, "100" is the number of inactive cycles launched [6], was used to calculate the criticality with specified positions of the control and protective rods in the experiment, as well as to calculate the excess reactivity in the case when all the control rods are 100% raised (120 cm + 11.4 cm = 131.4 cm above the lower boundary of the subcritical system).

According to the obtained results, the values calculated using Serpent exceed the experimental values, namely:

1. The average for all cases of KUCA configurations difference between the effective multiplication factors calculated in Serpent and the experimental values is 0.0072.

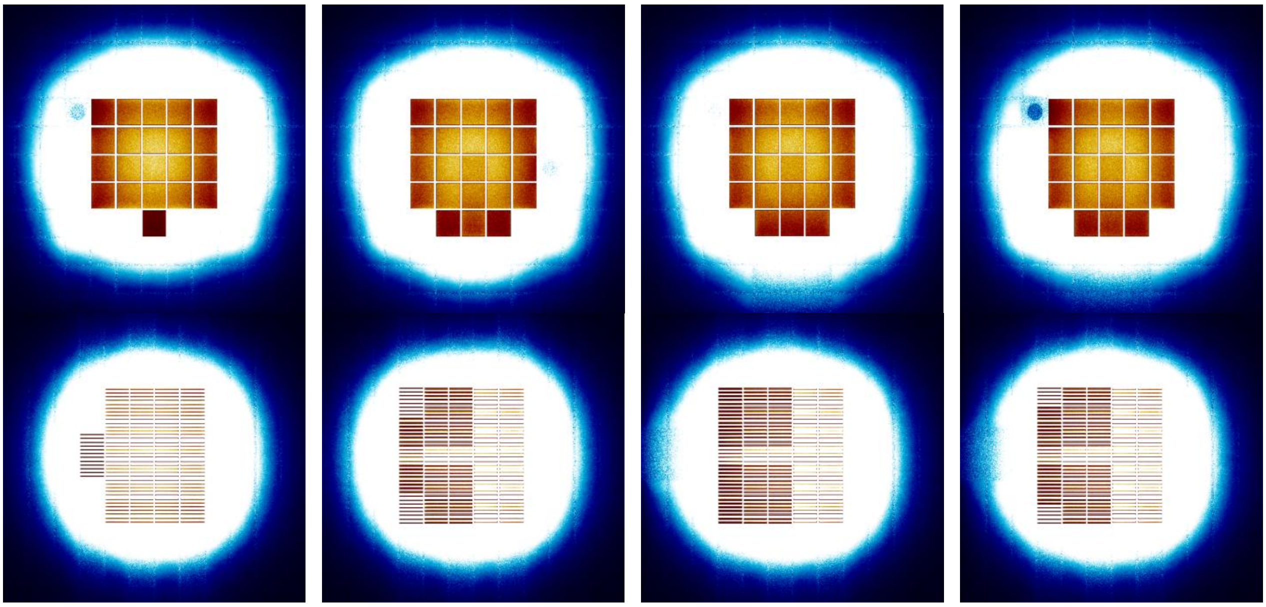
2. The maximum K_{eff} discrepancy between the Serpent and the experimental values is 0.00862.

3. The minimum K_{eff} discrepancy between the Serpent and the experimental values is 0.00504.

Statistical deviation in K_{eff} calculation in Serpent is 0.04%. The number of neutron histories tracked in one calculation corresponds to $1E{\cdot}10^7$.

The version of the calculation code “Serpent 2.1.26” was used in the Serpent calculation.

Fig. 2 shows the Serpent-visualization of the scattering (“cold” tones) and division (“warm” tones) reactions distribution for critical states of configurations II-1–II-4.



KUCA configuration II-1 *KUCA configuration II-2* *KUCA configuration II-3* *KUCA configuration II-4*

Fig. 2. Serpent-visualization of the density distribution of scattering (“cold” tones) and division (“warm” tones) reactions for configurations of KUCA II-1–II-4 calculation models

Also, in the context of cooperation with the Bariloche Atomic Center (Argentina), the Serpent results were compared (Table 4) with the results of the calculations performed in MCNP6 and KENO-VI by Dr. Francisco Leszczynski (Bariloche Atomic Center, Argentina) [5].

Table 4

Difference between the values of the effective multiplication factor of series II calculated in Serpent, MCNP6 and KENO-VI

Experiment (configuration)	Difference in results	Subcritical state (s.s.)	Critical state (c.s.)	Supercritical state (sup.s.)
		K_{eff}	K_{eff}	K_{eff}
II-1	MC-Se	-0.00095	-0.00164	-0.00176
	KE-Se	–	-0.00745	–
II-2	MC-Se	-0.00109	-0.00152	-0.00211
	KE-Se	–	-0.00807	–
II-3	MC-Se	-0.00117	-0.00162	-0.00164
	KE-Se	–	-0.00810	–
II-4	MC-Se	-0.00179	-0.00141	-0.00144
	KE-Se	–	-0.00816	–

Note (to Table 4): (MC-Se) – difference between the results of the MCNP calculation and the results of the Serpent calculation; (KE-Se) – difference between the results of the KENO-VI calculation and the results of the Serpent calculation.

The results of the calculation analysis of series II KUCA experiments performed using MCNP6 and KENO-VI determined that:

1. The average for all cases of KUCA configurations difference between the effective multiplication factors calculated in Serpent and MCNP is 0.00151.

2. The maximum K_{eff} discrepancy between Serpent and MCNP is 0.00211.

3. The minimum discrepancy between Serpent and MCNP is 0.00095.

4. The average for all cases of KUCA configurations difference between the effective multiplication factors calculated in Serpent and KENO-VI is 0.00795.

Analysis of the experiments II-2, II-3, II-4 performed using KENO-VI was carried out only for the critical state.

Statistical deviation in the K_{eff} calculating in MCNP is 0.008%. The number of neutron histories tracked in one calculation corresponds to $1 \cdot 10^8$ [5].

Statistical deviation in the K_{eff} calculation in KENO-VI is 0.02%. The number of neutron histories tracked in one calculation corresponds to 2.5 $E \cdot 10^7$ [5].

For MCNP and KENO-VI modeling Argentines used a newer library of estimated nuclear data ENDF/B-VII.1 and a modern library of thermal neutron scattering in polyethylene ENDF71SaB poly.20t [14].

From the above modeling, we can conclude that the Serpent results give a fair calculation accuracy and are quite close to those obtained in the modeling in MCNP and at the same time less close to the results obtained in KENO-VI. A similar relationship between the results obtained using the MCNP and Serpent calculation codes was also observed when calculating the effective multiplication factors for other subcritical systems: VENUS [9] and YALINA [13]. In the above articles, the results of the Serpent calculation also exceeded the results obtained in MCNP.

CONCLUSIONS

In this paper the calculation of the effective multiplication coefficients for configurations of the KUCA system from II-1 to II-4 using the Monte-Carlo Serpent code was carried out.

The results of the Serpent modeling were compared with the experimental data and the modeling results performed in other Monte Carlo codes: MCNP6 and KENO-VI.

The analysis of the obtained results shows that the Serpent modeling results are in worse agreement with the experimental data than the results of the MCNP6 modeling. Although the difference with the MCNP6 modeling can be explained by the fact that a newer library of thermal neutron scattering in polyethylene was used than in the Serpent calculation. At the same time, the results of KENO-VI modeling are more different from the results of MCNP6 and Serpent.

Monte Carlo Serpent code 2.1.26. can be used for further modeling and calculation analysis of new configurations of the KUCA Kyoto University subcritical system simultaneously with MCNP6 and KENO-VI, in order to investigate the existing differences in the results, or as an analogue of MCNP6 with account for the differences presented in the article. Using Serpent 2.1.26 as an analogue of KENO-VI is currently not recommended without additional research according to the obtained results.

Monte Carlo Serpent code can be successfully applied to the modeling of domestic projects of subcritical systems [15–18].

The authors would like to express gratitude to Dr. Francisco Leszczynski (Bariloche Atomic Center, Argentina) for the help in preparing this article and presenting the calculation data in MCNP6 and KENO-VI and to Dr. Cheol Ho Pyeon (Kyoto University, Reactors Research Institute, Japan) for presenting the experimental data.

This research was carried out with the financial support of the IAEA, within the terms and conditions of the Research Contract 20638 in the framework of the Coordinated Research Project (CRP) “Accelerator Driven Systems (ADS) Applications and use of Low-Enriched Uranium in ADS (T33002)” within the project “The Two-Zone Subcritical Systems with Fast and Thermal Neutron Spectra for Transmutation of Minor Actinides and Long-Lived Fission Products”.

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Article received 14.02.2019

ИСПОЛЬЗОВАНИЕ МОНТЕ-КАРЛО КОДА SERPENT ДЛЯ МОДЕЛИРОВАНИЯ ВТОРОЙ СЕРИИ ЭКСПЕРИМЕНТАЛЬНЫХ ДАННЫХ ПОДКРИТИЧЕСКОЙ УСТАНОВКИ KUCA

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С помощью Монте-Карло кода Serpent выполнено моделирование размножающих свойств подкритической установки Киотского университета KUCA. Рассчитаны эффективные коэффициенты размножения для критических экспериментов серии II на исследовательской подкритической установке KUCA. Представленные результаты сравнивались с экспериментальными расчетами и расчетами, выполненными с помощью Монте-Карло кодов MCNP6 и KENO-VI.

ВИКОРИСТАННЯ МОНТЕ-КАРЛО КОДУ SERPENT ДЛЯ МОДЕЛЮВАННЯ ДРУГОЇ СЕРІЇ ЕКСПЕРИМЕНТАЛЬНИХ ДАНИХ ПІДКРИТИЧНОЇ УСТАНОВКИ KUCA

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За допомогою Монте-Карло коду Serpent виконано моделювання розмножуючих властивостей підкритичної установки Кіотського університету KUCA. Розраховані ефективні коефіцієнти розмноження для критичних експериментів серії II на дослідницькій підкритичній установці KUCA. Представлені результати було порівняно з експериментальними розрахунками і розрахунками, виконаними за допомогою Монте-Карло кодів MCNP6 і KENO-VI.