SECTION 2

PROBLEMS OF MODERN NUCLEAR POWER ENGINEERING

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THE DEVELOPMENT OF A THREE-DIMENSIONAL MODEL OF WWER-1000 CORE USING THE MONTE CARLO SERPENT CODE FOR NEUTRON-PHYSICAL MODELING

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The article presents the use of the new Monte Carlo Serpent code for 3D modeling of the WWER-1000 reactor core. Core models for the first loading of RNPP4 and the 28th loading of SUNPP3, the fuel assemblies' models of different manufacturers were developed and presented. Considerable attention was paid to the detailed modeling of the upper, lower and side reflectors. Validation calculations of the Monte Carlo Serpent code for the WWER-1000 reactor were performed on the basis of the first RNPP4 loading. For the 28th loading of SUNPP3, albedo coefficients for radial and axial reflectors were obtained.

INTRODUCTION

Nuclear energy further development is impossible without the introduction of new computer codes based on more accurate methods for nuclear reactors calculation. The use of such codes will ensure reliable and safe operation of nuclear power plants [1]. It is very important to understand the change in the characteristics of the core during the fuel campaign when a nuclear reactor is operating. These characteristics may include the distribution of energy release in the core, the distribution of the neutron flux density in the reactor, temperature fields and changes in the isotopic composition. All these characteristics are very important for assessing the safe operation of nuclear power plants. A three-dimensional calculation of the nuclear reactor core, including modeling of neutron transport, heat transfer, and changes in the isotopic composition provides the ability to determine the above characteristics of nuclear fuel at any point in the core.

At the moment there are many computer codes designed for two-dimensional and three-dimensional core calculation [2, 3]. A variety of approaches and methods for modeling neutron transport in a nuclear reactor are used in them. In addition, various libraries of evaluated nuclear data are used for the modeling. As a result, the modeling results can be compared with the operational data of the NPP and the modeling results in other neutron-physical codes. Such comparative calculations in foreign literature are called benchmark modeling and cross-verification [4].

With the increase in the calculation power of modern computers, more and more attention is paid to the possibility of using computerized neutron-physical codes based on such stochastic methods, such as the Monte Carlo method [5]. Such codes make it possible to work with various materials and isotopes, complex geometry and provide the ability to determine various neutron-physical characteristics at any point of the model.

The article presents the application of the Monte Carlo Serpent code aimed to create a three-dimensional model and the subsequent calculation of the neutron-physical parameters of the WWER-1000 reactor core [6]. The modeling features of fuel assemblies, cores and reflection shield are considered using the Monte Carlo Serpent code. The first modeling results are presented.

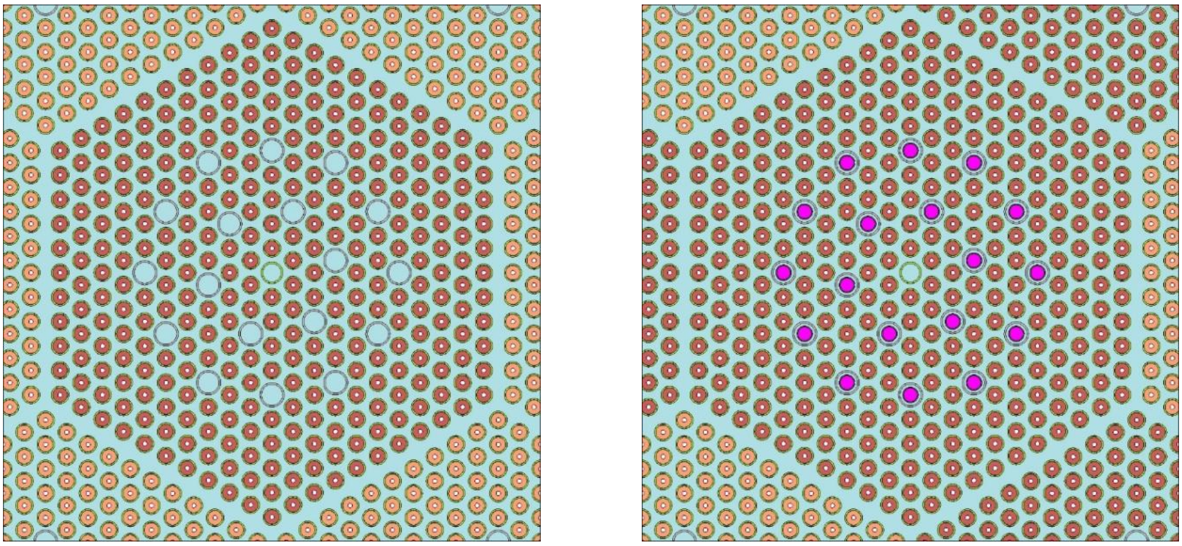
1. SERPENT CALCULATION CODE

The development of the Monte Carlo Serpent code started at the VTT Technical Research Center (Finland) in 2004. Serpent found favor in the eyes of many scientists around the world due to its convenience, accuracy of calculations and ability to solve a wide range of tasks [6]. Today Serpent is actively used for modeling reactors on both "fast" and "thermal" neutrons [7, 8]. The first version is available for free use for scientific purposes and is disseminated through the NEA Data Base.

Serpent is primarily used for tasks related to the preparation of low-group homogenized macroscopic characteristics for deterministic codes that solve the problem of calculating the entire core of a nuclear reactor. Serpent has a burnup module that makes it possible to model the change in the isotopic composition over time. Serpent code is actively used for the three-dimensional calculation of nuclear reactors in order to obtain pin-factors and albedo coefficients [9]. The only significant drawback of Serpent code is the lack of a thermal-hydraulic module, which would allow taking temperature feedback into account during the burnup calculation in the entire volume of the core.

2. SERPENT MODEL OF WWER-1000 REACTOR

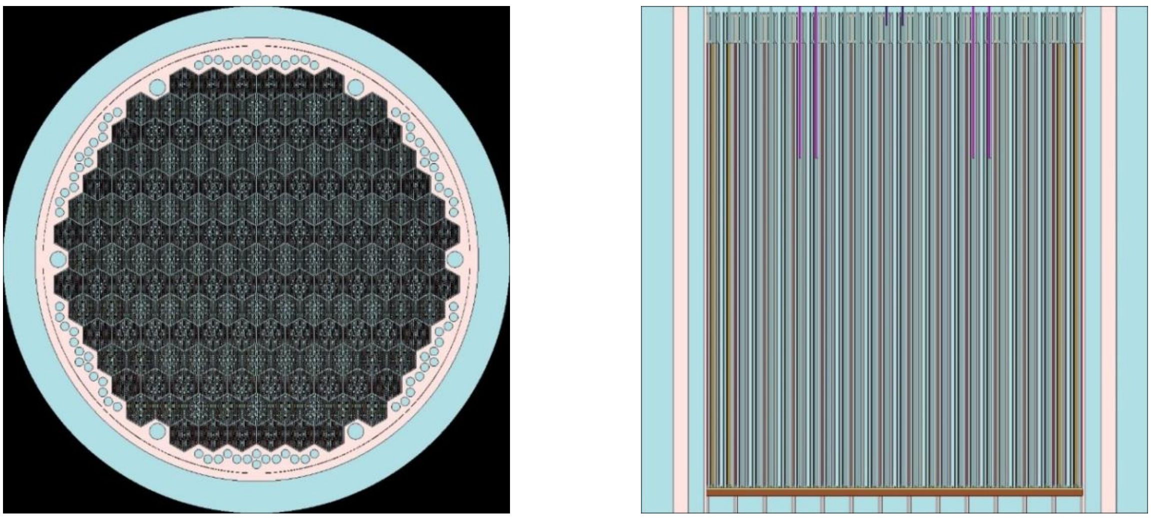
In the preparation of the presented article, three-dimensional models of cores of the first fuel load RNPP4 and the 28th fuel load SUNPP3 were developed. Since Serpent code has a wide range of tools for using various types of geometry, various input data (loading maps) were used to construct the hexagonal geometry of the fuel assembly and the core in the developing the three-dimensional model of the core. Also, reflection shield, upper and lower reflectors were modeled with high details. Thanks to the Serpent toolkit, it is possible to form complex geometry from the smaller ones separately and from the preformed parts. For example, fuel rods, gadolinium fuel rods, central tubes, instrumental channels, absorbing rods are modeled using the "pin" function ("pins"). In turn, the pins were used to form different types of fuel assemblies using the "lat" ("lattice") function. At the final stage, also by using the "lat" function, cartograms of cores were formed. So for the first loading of the RNPP4, four types of fuel assemblies were modeled, namely: 16FL, 30FL, 42FLB, 44FLB. In Fig. 1 shows FA 30FL (a) and FA 30FL (b) with immersed absorbing rods of the control system CPS of the tenth group.



a *b*

Fig. 1. Serpent visualization FA 30FL (central plane) with raised control rods (a) and immersed control rods (b)

Serpent code provides the ability to form FA geometry with upper and lower reflectors using the "lat-9" ("ninth type lattice") function – the so-called "vertical stack". In the presented model, the lower reflector has a height of 23.1 cm (counting from the lower border of the fuel column), the reflector is divided into six different layers, which cover the fuel element tips, the lower grid, part of the fuel assembly bottom nozzle and part of the supporting bucket. The upper reflector has a height of 29.4 cm (counting from the upper boundary of the fuel column) and is divided into five layers, which cover the fuel element tips and two upper spacer grids. The remaining 13 spacer grids, which are located in the zone of the fuel column, are accounting on the principle of an additional layer of material from the spacer grids on the surface of fuel element, gadolinium fuel element, guide channels and central tube. Fig. 2 shows a horizontal cross-section of core of the RNPP4 (a) first loading and a vertical cross-section of core of the RNPP4 (b) first loading. The core model is designed in such a way that it can be used to calculate the boundary conditions for the ImCore national calculation deterministic code, which is developed in PJSC "SRPA "Impulse". The boundary conditions are planned to be calculated in two variants: 1) albedo coefficients (ratio of neutron currents at the border: core is the reflector); 2) group constants for two rows of six-sided prisms (with a "flat-to-flat" size of similar fuel assemblies) surrounding the core and forming the reactor reflection shield.

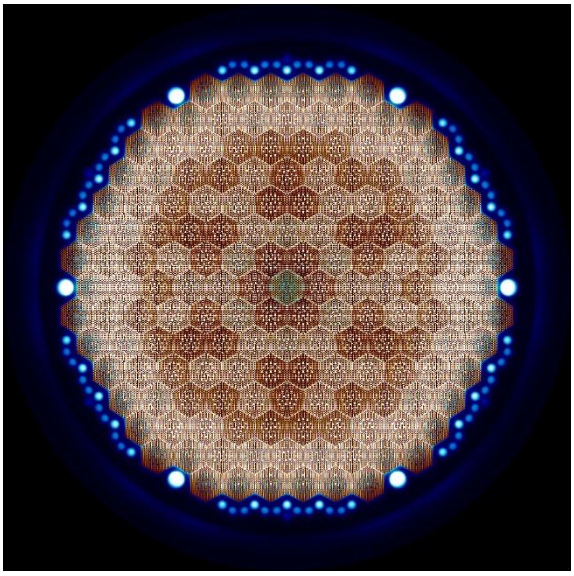


a *b*

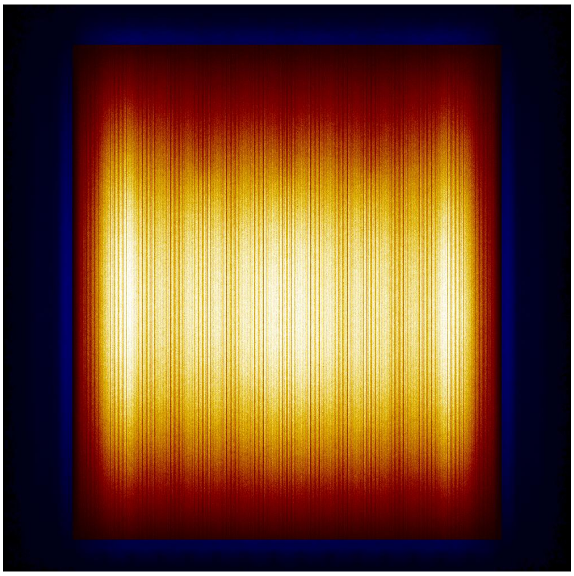
Fig. 2. Serpent visualization of the first RNPP4 fuel loading in horizontal cross-section X-Y (a) and vertical cross-section X-Z (b)

3. RESULTS OF SERPENT MODELING

Modeling and calculation of the critical state of core of the RNPP4 first loading for the hot zero power in the Serpent code was performed in order to validate the Serpent and substantiate further core calculations of WWER-1000 reactors. This work was carried out in collaboration with the research centers Helmholtz-Zentrum Dresden-Rossendorfin (Germany) and VTT Technical Research Center of Finland Ltd (Finland, Serpent developers) whose specializations are: calculations of thermal/fast neutron reactors. The calculation was performed using the "set pop 1000000 1000 20" option, where "1000000" is the number of neutrons per cycle, "1000" is the number of active cycles launched, and "20" is the number of inactive cycles launched. The latest version of the Serpent 2.1.30 calculation code is used in the calculation in Serpent. To perform the modeling, a computational server was used with the following parameters: Intel (R) Core (TM) i5-6600K CPU @ 3.50GHz processor and 32 GB RAM. As a result, the value of the effective multiplication factor of 1.00162 with a statistical error of 0.00002 was obtained. The obtained results give grounds to consider the developed model of the core of a WWER-1000 reactor suitable for the neutron-physical calculations. Fig. 3 shows the so-called "mesh" visualization using the Serpent code for the RNPP4 first loading, where warm tones (red-yellow) reflect the "density of fission reactions", and cold tones (blue-white) reflect the "density of scattering reactions".



a



b

Fig. 3. Serpent-"mesh"-visualization of the calculation of the RNPP4 first fuel loading in the horizontal cross-section X-Y (a) and the vertical cross-section X-Z (b)

Core modeling in the Serpent code for the 28th loading of SUNPP3 was performed to determine the albedo coefficients used to form the boundary conditions in the ImCore deterministic code, which is developed in PJSC "SRPA "Impulse" for the needs of the Ukrainian NPPs. As a basis, the above model RNPP4 was used. As a result of Serpent modeling, albedo coefficients for each of the 90 side faces of the core and albedo coefficients for the upper and lower reflectors can be obtained both for the entire core and for each of the 163 FA. Table shows the obtained by Serpent calculation albedo coefficients of the 28th SUNPP3 loading for 90-degree symmetry (fast and thermal neutron energy groups).

Albedo coefficients for 90-degree symmetry for two neutron energy groups

Face number	Albedo coefficients		Face number	Albedo coefficients	
	Fast group	Thermal group		Fast group	Thermal group
1	0.7038	0.7695	13	0.6495	0.6571
2	0.6472	0.6605	14	0.7026	0.7545
3	0.6940	0.7262	15	0.5901	0.8605
4	0.6185	0.7358	16	0.7017	0.7652
5	0.6435	0.7481	17	0.6490	0.6593
6	0.6290	0.7460	18	0.6979	0.7256
7	0.6333	0.7508	19	0.6165	0.7450
8	0.6325	0.7401	20	0.6446	0.7455
9	0.6291	0.7403	21	0.6310	0.7381
10	0.6426	0.7448	22	0.6336	0.7490
11	0.6186	0.7423	23	0.6297	0.7376
12	0.6981	0.7246	-	-	-

CONCLUSIONS

The Monte Carlo code Serpent is used for the three-dimensional modeling of the WWER-1000 reactor core. In the presented work, core models were developed for the first RNPP4 loading and for the 28th SUNPP3 loading. Validation calculations of the Monte Carlo code Serpent of the WWER-1000 reactor were made on the basis of the first RNPP4 loading. For the 28th SUNPP3 loading, albedo coefficients for radial and axial reflectors were obtained.

REFERENCES

1. G. Li, X. Wang, B. Liang, X. Li, et al. Modeling and control of nuclear reactor cores for electricity generation: A review of advanced technologies // *Renewable and Sustainable Energy Reviews*. 2016, v. 60, p. 116-128.
2. U. Rohde, S. Kliem, U. Grundmann, et al. The reactor dynamics code DYN3D – models, validation and applications // *Progress in Nuclear Energy*. 2016, v. 89, p. 170-190.
3. B.A. Lindley, J.G. Hosking, P.J. Smith, et al. Current status of the reactor physics code WIMS and recent developments // *Annals of Nuclear Energy*. 2017, v. 102, p. 148-157.
4. V.V. Galchenko, V.I. Gulik, I.I. Shlapak. Using of the Serpent code based on the Monte-Carlo method for calculation of the VVER-1000 fuel assembly characteristics // *Nuclear Physics and Atomic Energy*. 2016, v. 17(3), p. 250-258.
5. J. Leppänen, M. Pusa, E. Fridman. Overview of methodology for spatial homogenization in the Serpent 2 Monte Carlo code // *Annals of Nuclear Energy*. 2016, v. 96, p. 126-136.
6. J. Leppänen, M. Pusa, T. Viitanen, et al. The Serpent Monte Carlo code: Status, development and applications in 2013 // *Annals of Nuclear Energy*. 2015, v. 82, p. 142-150.
7. V.M. Khotyayintsev, A.V. Aksonov, O.M. Khotyayintseva, et al. Velocity Characteristic and Stability of Wave Solutions for a CANDLE Reactor with Thermal Feedback // *Annals of Nuclear Energy*. 2015, v. 85, p. 337-345.
8. V.V. Galchenko, I.I. Shlapak, V.I. Gulik. The computational benchmark for fuel assembly of VVER-1000 with using Monte Carlo Serpent code // *Nuclear Technology & Radiation Protection*. 2018, v. 33(1), p. 24-30.
9. C. Ipbüker, H. Nulk, V. Gulik, et al. Radiation shielding properties of a novel cement-basalt mixture for nuclear energy applications // *Nuclear Engineering and Design*. 2015, v. 284, p. 27-37.

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РАЗРАБОТКА ТРЕХМЕРНОЙ МОДЕЛИ РЕАКТОРА ВВЭР-1000 С ПОМОЩЬЮ МОНТЕ-КАРЛО КОДА SERPENT ДЛЯ НЕЙТРОННО-ФИЗИЧЕСКОГО МОДЕЛИРОВАНИЯ

В.И. Гулик, А.Р. Трофименко, В.В. Гальченко, Д.В. Будик

Представлено использование нового Монте-Карло кода Serpent для трехмерного моделирования активной зоны реактора ВВЭР-1000. Разработаны и представлены модели активных зон первой загрузки РАЭС4 и 28-й загрузки ЮУАЭС3, модели ТВС различных производителей. Значительное внимание было уделено детальному моделированию верхнего, нижнего и бокового отражателей. Валидационные расчеты Монте-Карло кода Serpent для реактора типа ВВЭР-1000 выполнены на основе первой загрузки РАЭС4. Для 28-й загрузки ЮУАЭС3 были рассчитаны коэффициенты альбедо для радиального и аксиальных отражателей.

РОЗРОБКА ТРИВИМІРНОЇ МОДЕЛІ РЕАКТОРА ВВЕР-1000 ЗА ДОПОМОГОЮ МОНТЕ-КАРЛО КОДУ SERPENT ДЛЯ НЕЙТРОННО-ФІЗИЧНОГО МОДЕЛЮВАННЯ

В.І. Гулік, О.Р. Трофименко, В.В. Гальченко, Д.В. Будік

Представлено використання нового Монте-Карло коду Serpent для тривимірного моделювання активної зони реактора ВВЕР-1000. Розроблено і представлено моделі активних зон для першого завантаження РАЕС4 та 28-го завантаження ЮУАЕС3. При цьому було підготовлено моделі ТВЗ різних виробників. Значну увагу приділено детальному моделюванню верхнього, нижнього та бічного відбивачів. Валідаційні розрахунки Монте-Карло коду Serpent для реактора типу ВВЕР-1000 було виконано на основі першого завантаження РАЕС4. Для 28-го завантаження ЮУАЕС3 було розраховано коефіцієнти альбедо для радіального та аксіальних відбивачів.