The Modeling of kinetic characteristics of subcritical assembly “Yalina” using SuperMC Monte Carlo code

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Abstract. Accelerator-driven systems (ADS) are considered to be promising for energy generation and transmutation of the long-live radiotoxic nuclides contained in spent nuclear fuel. The Yalina assembly has the same conceptual construction with a neutron generator coupled to a subcritical core. The major difference between ADS and Yalina experiments is that the neutron energy spectrum of the Yalina core is thermal. The simulation of the Yalina-Thermal experimental program was conducted via new neutron-physics code SuperMC developed by the FDS Team in China. SuperMC is a CAD-based Monte Carlo program for integrated simulation of nuclear systems by making use of hybrid Monte Carlo and deterministic methods and advanced computer technologies. The calculations were held with the use of the up to date nuclear data libraries ENDF/B-VII.1, ENDF/B-VIII, FENDL 3.0, JEFF 3.3, JENDL 4.0. The effective multiplication constant, $k_{\text{eff}}$, and the fraction of delayed neutrons, $\beta_{\text{eff}}$, were calculated for the 285 fuel rod configuration of the Yalina-Thermal subcritical assembly. Evaluation of the Yalina-Thermal experimental program using SuperMC code has been made for the first time in this work.

1. Introduction
Accelerator-driven systems (ADS) are considered to be promising for energy generation and transmutation of long-live radiotoxic nuclides contained in spent nuclear fuel [1]. The Yalina facility has the same conceptual construction with a neutron generator coupled to a subcritical core [2]. The major difference between ADS and Yalina experiments is that the neutron energy spectrum of the Yalina core is predominantly thermal. Yalina does not fulfill the conceptual design of a future ADS, but the neutronics of the subcritical core is an interesting feature since the methods described are applicable in both fast and thermal systems independent of the type of neutron source.

The study of the neutronics of Yalina-Thermal was carried out earlier and the results of calculations were obtained numerically by different Monte Carlo codes for a number of experiments [3].

In this study the SuperMC Monte Carlo code [4] was used for calculating the kinetic parameters of the Yalina-Thermal subcritical assembly with 10% enrichment uranium oxide fuel and polyethylene moderator for 285 fuel rods core configuration. Up to date nuclear data libraries ENDF/B-VII.1, ENDF/B-VIII [5], FENDL 3.0 [6], JEFF 3.3 [7], JENDL 4.0 [8] were used in calculations.
2. The Yalina-T subcritical assembly
Yalina is a zero-power subcritical facility operating in the State Scientific Institution “Joint Institute for Power and Nuclear Research – Sosny” of the National Academy of Sciences of Belarus. The facility consists of two subcritical assemblies Yalina-Thermal (hereinafter referred to as Yalina-T) and Yalina-Booster, a neutron generator NG-12-1, a measuring complex and vital support system. The facility is used to study neutronics and kinetics of subcritical multiplying systems with thermal and fast neutron spectra driven by an external source. Measurements of the transmutation reaction rates for long-lived fission products and minor actinides are also held at the facility as well as other related studies.

A general view of the core of Yalina-T subcritical assembly is shown at Fig 1. The exact dimensions of the core and structural elements are available in the published report [9].

![Figure 1. Scheme of the sub-critical assembly Yalina-T: 1 – graphite block, 2 – cadmium screen, 3 – case, 4 – neutron source supply channel, 5 – polyethylene block, 6 – CPS block, 7 – neutron detector, 8 – lead target, 9 – locking element, 10 – experimental channel, 11 – cable conduit, 12 – compensating controls, 13 – servo drive of a neutron source, 14 – container of a neutron source, 15 – neutron source, 16 – shutter, 17 – shutter drive.](image)

3. SuperMC Monte Carlo code
SuperMC (Super Monte Carlo Simulation Program for Nuclear Design and Safety Evaluation) developed by the FDS Team at the Institute of Nuclear Energy Safety Technology of the China Academy of Sciences is a CAD-based Monte Carlo program for integrated simulation of nuclear systems by making use of hybrid Monte Carlo and deterministic methods and advanced computer technologies [10].

SuperMC makes use of Monte Carlo transport methods of neutron and photon with series of novel acceleration methods for transport calculation.

Advanced features of SuperMC program are CAD-based automatic geometry and physics modelling with high efficiency and precision, multi-dimensional and multi-style intelligent visualization analysis and automatic modelling, efficient computation and visualization analysis based on cloud computing [10].

Publicly available version of SuperMC 3.3 can accomplish the transport calculation of n, γ and can be applied for criticality and shielding design of reactors [10].

4 Calculation
For the purposes of this work, a computer model of Yalina-T subcritical assembly was built for the base assembly configuration, which includes 285 uranium-oxide fuel rods with 10% enrichment without the neutron absorber rods.

The computational model of the Yalina-T stand was created according to the description of the installation in the report [9]. All the main parameters such as spatial dimensions of the assembly core elements were precisely transferred to the computer model without any simplifications affecting the final result of the calculation. The isotopic composition of the assembly materials was specified in accordance with the data in the appendix to [9]. Separate calculations have shown that the presence or absence of structural materials outside the boundaries of the graphite reflector in the computer model of the assembly does not affect the values of $k_{\text{eff}}$. Calculations were carried out for the assembly under normal conditions (temperature 300 K). The control rods were fixed in the withdrawn position. An isotropic point source based on $^{252}$Cf fission spectrum, placed in the geometric center of the core of the assembly was specified in the computer model as an external source of neutrons for the calculating purposes.

5 Results Obtained
Calculations were made using ENDF/B-VII.1, ENDF/B-VIII, FENDL 3.0, JEFF 3.3, JENDL 4.0 nuclear data libraries. The results of calculating the neutron-physical characteristics of the Yalina-T assembly using various libraries of evaluated nuclear data and the corresponding statistical errors of the Monte Carlo calculation are shown in Tab 1 and Tab 2.

The results of the effective multiplication constant calculated were compared with $k_{\text{eff}}$ result $0.9569 \pm 0.0018$ published in [11] which was obtained as an average result by means of 3 different experimental methods.

Table 1. Results of calculating the neutron-physical characteristics of the Yalina-T assembly for a configuration with 285 fuel rods using SuperMC code.

| Nuclear Data Library | $k_{\text{eff}}$        | $\beta_{\text{eff}}$ |
|----------------------|-------------------------|-----------------------|
| ENDF/B-VII.1         | 0.95314 ± 0.00003       | 0.00723 ± 0.00063     |
| ENDF/B-VIII.0        | 0.95626 ± 0.00003       | 0.00718 ± 0.00063     |
| FENDL 3.0            | 0.95028 ± 0.00003       | 0.00720 ± 0.00064     |
| JEFF 3.3             | 0.94742 ± 0.00003       | 0.00759 ± 0.00062     |
| JENDL 4.0            | 0.95215 ± 0.00003       | 0.00722 ± 0.00064     |

Table 2. Results of calculating the neutron-physical characteristics of the Yalina-T assembly for a configuration with 285 fuel rods using SuperMC code.

| Nuclear Data Library | $k_{\text{eff}}$ Calculated | $k_{\text{eff}}$ Experimental | Calculating Accuracy |
|----------------------|------------------------------|------------------------------|----------------------|
| ENDF/B-VII.1         | 0.95314 ± 0.00003            | 0.9569 ± 0.0018              | 0.39%                |
| ENDF/B-VIII.0        | 0.95626 ± 0.00003            | 0.9569 ± 0.0018              | 0.07%                |
| FENDL 3.0            | 0.95028 ± 0.00003            | 0.9569 ± 0.0018              | 0.69%                |
| JEFF 3.3             | 0.94742 ± 0.00003            | 0.9569 ± 0.0018              | 0.99%                |
| JENDL 4.0            | 0.95215 ± 0.00003            | 0.9569 ± 0.0018              | 0.49%                |

SuperMC Monte Carlo code gives an option to view and analyse the results obtained in visualization mode. Fig 2 shows the color-rendered spatial neutron flux distribution inside of the Yalina-T assembly core. One can note the symmetric distribution of the neutron flux with respect to the Z axis, along which the fuel rods are directed, and a rectangular parallelepiped-shaped zone in the
central region for installing a target for deuterons. The lowest neutron flux, as depicted in blue in Fig 2, is at the periphery at the corners of the core.

![Neutron flux spatial distribution](image)

**Figure 2.** Neutron flux spatial distribution (visualization by means of SuperMC).

### 6 Conclusion

In this work, a computer model of a physical experiment at the Yalina-T has been built using the SuperMC Monte Carlo code. Calculations of the neutron-physical characteristics of the Yalina-T subcritical assembly in a configuration with 285 fuel rods were performed using the latest versions of FENDL, ENDF, JEFF and JENDL nuclear data libraries.

The effective multiplication constant, $k_{\text{eff}} = 0.95626 \pm 0.00003$ and the fraction of delayed neutrons $\beta_{\text{eff}} = 0.00718 \pm 0.00063$ were calculated using ENDF/B-VIII.0 nuclear data library. The values obtained are in good agreement with the experimental ones; the discrepancy between the calculated and experimental values in the effective neutron multiplication factor does not exceed 1%.

Comparison of these results independently obtained using SuperMC with the results obtained earlier using experimental methods the conclusion can be made about the compliance of the Yalina-T experimental nuclear experimental facility with nuclear safety requirements, as well as the validity of the SuperMC Monte Carlo code for calculating of neutron-physical parameters of nuclear facilities with polyethylene moderator similar in design, size and parameters with subcritical assembly Yalina-T.

Further research will be aimed at analyzing the influence of uncertainties in specifying the geometry and material composition of assembly elements on the calculation result. SuperMC Monte Carlo code can be used as computational accompaniment for experiments at the Yalina nuclear facility, including the studying of the influence of spatial effects.

### References

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