Yalina-thermal facility neutron characteristic computational study

^{129}I, ^{237}Np and ^{243}Am transmutation reaction rates calculations

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Abstract. Present work describes Monte-Carlo calculations of the neutron field and minor actinide transmutation reaction rates within the Yalina-Thermal sub-critical assembly of the Joint Institute for Power and Nuclear Research – Sosny of the National Academy of Sciences of Belarus. The computer model of the facility was prepared for the corresponding calculations via MCU-PD and MCNP Monte-Carlo codes. The model neutron characteristics estimations were performed as well as the nuclear safety analysis. The up-to-date ENDF B/VIII, JEFF 3.3 and JENDL 4.0 nuclear data libraries were used during research.

1 Introduction

The demand for results of subcritical experiments is constantly increasing with rising requirements on computational codes and cross section libraries used to justify nuclear safety in activities associated with the use of nuclear energy (e.g. operating nuclear facilities and handling fissionable materials). At the Joint Institute for Power and Nuclear Research – Sosny (Belarus) sub-critical facility Yalina [1–4] been constructed for the ADS-system neutronic properties investigation. Yalina facility consists of two sub-critical assemblies Yalina-Thermal and Yalina-Booster, neutron sources (D(d,n)^{3}He, or T(d,n)^{4}He reactions, or ^{252}Cf spontaneous-fission), a measuring complex and a vital support system. Another feature that makes the sub-critical assembly a diverse research facility is a possibility to use different fuel loading configurations and number of fuel rods for measurements. A series of experiments to study I, Np and Am transmutation processes are prepared on the Yalina-Thermal assembly. Computer modeling and calculations are necessary for such an activity. Current work is aimed at Yalina-Thermal assembly computer modelling and neutron characteristics Monte-Carlo calculations. In order to satisfy the nuclear safety criteria and IAEA requirements [5] for sub-critical facilities the k_{eff} calculations and corresponding uncertainty analysis were performed. The most recent available versions of the nuclear data libraries (ENDF B/VIII [6], JEFF 3.3 [7] and JENDL 4.0 [8]) were used in calculations.

2 Experiment description

Yalina facility experiments are mainly focused on extensive measurements of neutron spectra, reactor kinetics, monitor detector system performance and transmutation rates. The Yalina facility is entirely underground and occupies several shielded vaults dedicated respectively to the control room, accelerator and beam transport system, two sub-critical assemblies, beam monitoring area, and additional areas for counting irradiated samples.

Yalina-Thermal and Yalina-Booster sub-critical assemblies are used in experiments with uranium fuel of different composition and enrichment. Yalina-Booster has a two-zone active core providing both fast and thermal neutron spectrum. Yalina-Thermal provides thermal neutron spectrum only. More detailed description is introduced in Argonne national laboratory report [9].

The neutron generator consists of a deuterium ions linear accelerator (deuterium energy 250 keV, el.current 1–10 mA) and the target block. The magnet system separates D positive ions with magnetic lenses. The neutron beam falls on a TiT 1.5–1.8 or TiD 1.5–1.8 target and generates neutrons in the D(d,n)^{3}He or T(d,n)^{4}He reactions. Neutrons have an energy of 14.1 MeV or 2.45 MeV respectively. Currently, two types of water-cooled targets with a diameter of 230 or 45 mm are used. For some experiments the ^{252}Cf is used as a neutron source.

2.1 Yalina-Thermal assembly

Yalina-Thermal assembly is a zero-power sub-critical assembly driven by a high-intensity neutron generator or a ^{252}Cf neutron source and provides a full thermal neutron spectrum in all its experimental channels. The assembly consists of the rectangular parallelepiped core with uranium dioxide (10% ^{235}U enriched) fuel rods in a polyethylene moderator and high-purity graphite reflector around it. The central part of the sub-critical assembly is a neutron producing lead target formed from 12 blocks that can be slipped into a square cross-section cavity, centered on the axis. The experimental channels for accommodating neutron flux monitoring detectors are located at the core boundaries. Three additional experimental channels are

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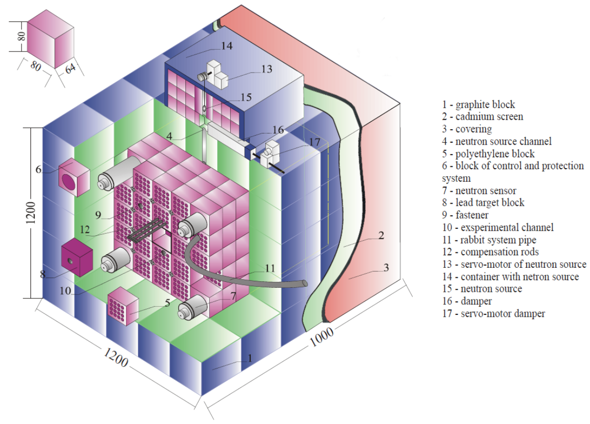


Figure 1: Yalina-Thermal 3D-view blueprint [9]

located within the assembly core: EC1 (core center), EC2 (core middle part) and EC3 (core periphery). The Yalina-Thermal 3D-view blueprint is shown on figure 1. The main parameters are presented in table 1.

Table 1: Yalina-Thermal assembly main design characteristics

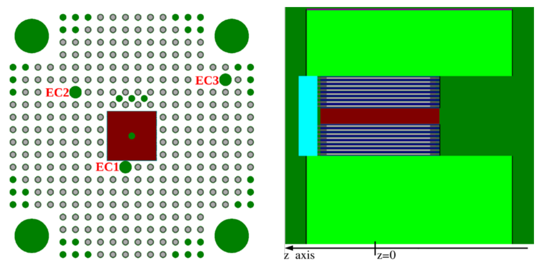
Fuel	*Moderator*	*Active zone*
Density 5.1 g/cm^3	Density 0.92 g/cm^3	Number of rods 280
Enrichment 10.0%	C mass fraction 85.7%	Lattice pitch 2.0 cm
Fuel mass 97.2 g	H mass fraction 14.3%	Neut. src. $2.2 \cdot 10^5$ $n/cm^2 s$

3 Calculations and results

3.1 Model description

The computer model of the Yalina-Thermal assembly was prepared on the basis of its description and data gained from experimenters. All main core parameters were transferred to the model without any significant simplification. The specific calculations showed no influence of the constructive materials beyond the reflector zone on the k_{eff} value so they were not included into the model. The final reference model visualization is shown on figure 2.

On the basis of the built Yalina-Thermal computer model the calculations of the k_{eff} value, neutron flux distribution and spectra, and transmutation reaction rates were calculated. Two Monte-Carlo codes were used for that purpose: MCU (Monte-Carlo Universe) of the NRC «Kurchatov Institute» [10] and MCNP (Monte-Carlo Nuclear Particles) of the Argonne national Laboratory [11]. For the purpose of obtaining the relevant results the up-to-date nuclear data libraries (ENDF B/VIII [6], JEFF 3.3 [7] and JENDL 4.0 [8]) were used in calculations. For the comparative analysis the additional calculations with previous versions of data libraries (ENDF B/VII.1 [12] and JEFF 3.1 [13]) were performed as well.



(a) core XY cross-section (b) full assembly YZ cross-section

Figure 2: Yalina-Thermal computer model visualization

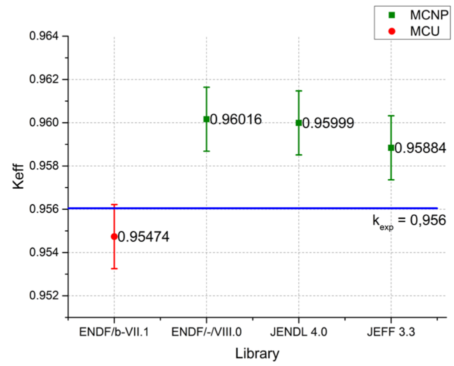


Figure 3: k_{eff} calculations

3.2 K_{eff} calculations

The nuclear safety assessment involves calculation of the k_{eff} value and its corresponding uncertainty analysis. In order to fulfill the IAEA requirements for nuclear safety on the sub-critical systems [5] the experimental value of the k_{eff} was maintained at 0.965 (< 0.98). The calculation of the model k_{eff} gives the average value of $k_{\mathrm{eff}} = 0.9600 \pm 0.0003$ (Monte-Carlo statistical error). The given value is consistent with previous calculations and experiments [2, 3] which had some significant discrepancy depending on the nuclear libraries versions used. The analysis of the uncertainty from the initial parameters gives total model uncertainty at $\delta k_{\mathrm{eff}} = \pm 0.003$.

The calculations for different nuclear libraries [6–8, 12] were carried out as well. The corresponding data shown on figure 3. The error bars on the graph show total uncertainty calculated for the model. All calculations showed that k_{eff} does not exceed 0.98 value, ensuring compliance with IAEA requirements [5].

The uncertainty analysis was performed for the first time and was evaluated under the guidelines [14]. Seven main input parameters were studied for their impact on total k_{eff} value within model calculations. Their mean value and standard deviation were chosen in accordance to the experiment descriptions [1–4] and guidelines [15]. Total k_{eff} uncertainty due to the input parameters inaccuracies was defined to be ±0.003. Initial parameters characteristics and their partial contributions to the total uncertainty are presented in table 2.

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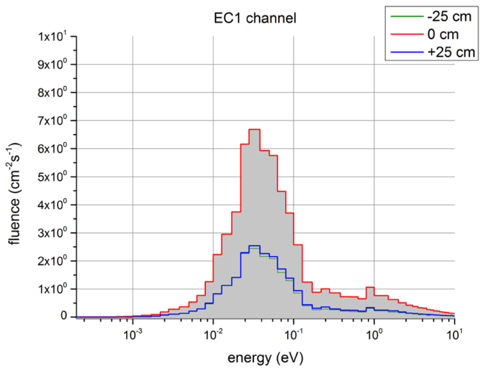
Table 2: Yalina-Thermal k_{eff} calculation uncertainties

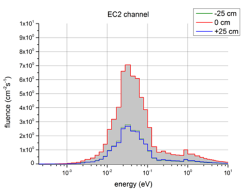
Parameter	*Mean value*	*Std. uncertainty*	$\Delta k_{\delta x_i} / \delta x_i$	Δk_{eff}
Enrichment,%	10.0	0.0067	0.0599	4.0031E-04
Fuel mass, g	97.2	0.0087	0.0520	4.5096E-04
Fuel height, cm	50.0	0.0333	0.0070	2.3375E-04
Fuel radius, cm	0.35	0.0289	0.0260	7.5230E-04
Clad thickness, cm	0.15	0.0289	0.0470	1.3601E-03
Lattice pitch, cm	2.0	0.1000	0.0106	1.0600E-03
Moderator density, g/cm^3	0.923	0.0200	0.1433	2.8664E-03

3.3 Neutron flux calculations

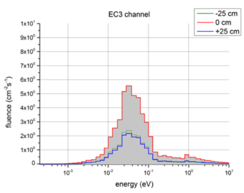
The Yalina-T has 3 experimental channels inside the core for detector and samples placing. For defining the optimal detector and sample placing the neutron flux and spectra calculations were held for these channels. The registration area was modeled on the basis of the data on scintillator sizes and Iodine, Neptunium and Americium samples sizes, used in series of experiments [1–4]. The corresponding data on the neutron flux and spectra calculations normalized for a single-born neuron for three experimental channels are shown on figure 4.



(a) EC1 channel flux



(b) EC2 channel flux



(c) EC3 channel flux

Figure 4: Neutron flux and spectra calculations for experimental channels

The ^{235}U fission rate and thermal neutron flux distributions over XY plane were reconstructed. The corresponding data shown on figure 5. The lighter areas of both cold and warm tones indicate higher neutron flux density and fission rate respectively.

3.4 I, Np and Am reaction rates calculations

The need to safely convert nuclear waste generated from fission nuclear power reactors to smaller volumes, with lower chemical and radioactive toxicity (radiotoxicity) is one of the essential challenges to resolve. Therefore the transmutation studies are held at the Yalina facility which require a computation background.

The transmutation reaction rates studies were performed via total neutron reaction rate calculations for ^{129}I, ^{237}Np and ^{241}Am isotopes (important for reactor physics). The computer model registration zones were chosen to match the experimental samples sizes. Calculations were fulfilled for up-to-date nuclear libraries [6–8]. All corresponding results are shown figure 6. The normalization of data was made for a single neutron emitted from a neutron source.

As can be seen the correlation between results from calculations with different nuclear data libraries rather solid. As no uncertainty quantification was made (except the statistical errors from Monte-Carlo calculations) additional studies must be held to determine the overlap regions.

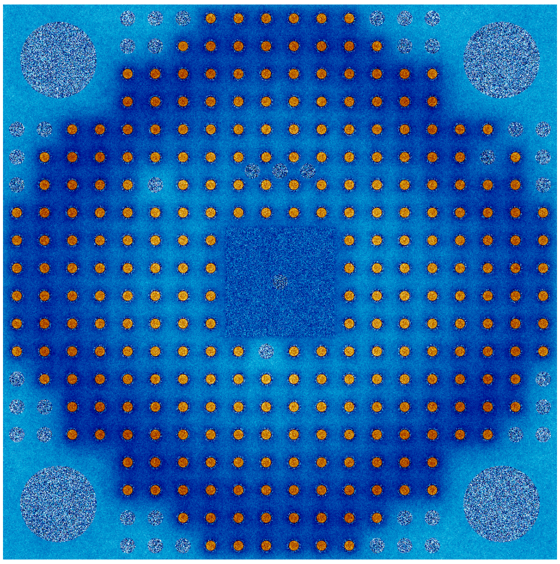
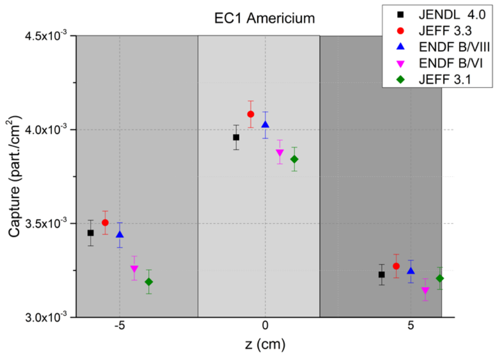


Figure 5: ^{235}U fission rate and thermal neutron flux distributions over XY plane (z=0)

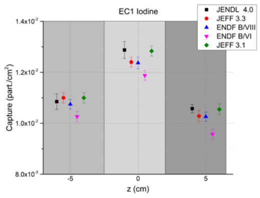
4 Discussion

Yalina-Thermal facility suggests a numerous data analysis for the ADS-systems studies and transmutation processes investigations. The main objective of this work is to reevaluate data on the k_{eff}, neutron flux and reaction rates calculations with the up-to-date nuclear libraries and Monte-Carlo codes in order to maintain relevance of the facility experiments.

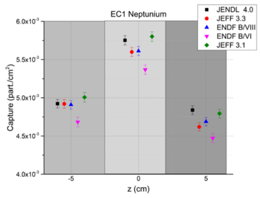
The most interesting values for the k_{eff} and neutron spectra parameters have been evaluated via MCU-PD and MCNP Monte-Carlo codes using ENDF B/VIII, JEFF 3.3 and JENDL 4.0 up-to-date nuclear libraries. The reaction rates for ^{129}I, ^{233}Np and ^{241}Am have been calculated as well. Further experiments and computer modeling aimed at deriving necessary data for sub-critical facilities and ADS-systems general studies.



(a) Americium



(b) Iodine



(c) Neptunium

Figure 6: Neutron capture reaction rates calculations

References

[1] I. Serafimovich, C. Routkovskaya, V. Bournos, H. Kiyavitskaya, Y. Fokov, S. Mazanik, S. Chigrinov, Y. Gohar, G. Aliberti, F. Kondev et al., *YALINA subcritical facility*, in *8th International Topical Meeting on Nuclear Applications of Accelerators, ACCAPP'07* (2007)

[2] H. Kiyavitskaya, Y. Fokov, Problems of Atomic Science and Technology, Ser. Thermonuclear Fusion **38**, 53 (2015)

[3] A. Talamo, Y. Gohar, H. Kiyavitskaya, V. Bournos, Y. Fokov, C. Routkovskaya, Nuclear Technology **184**, 131 (2013)

[4] V.A. Beresneva, T.N. Korbut, S.V. Korneyev, Physics of Atomic Nuclei **81**, 1441 (2018)

[5] *Safety of Research Reactors*, Number SSR-3 in Specific Safety Requirements (INTERNATIONAL ATOMIC ENERGY AGENCY, Vienna, 2016)

[6] D. Brown, M. Chadwick, R. Capote, A. Kahler, A. Trkov, M. Herman, A. Sonzogni, Y. Danon, A. Carlson, M. Dunn et al., Nuclear Data Sheets **148** (2018), special Issue on Nuclear Reaction Data

[7] O. Cabellos, F. Alvarez-Velarde, M. Angelone, C. Diez, J. Dyrda, L. Fiorito, U. Fischer, M. Fleming, W. Haeck, I. Hill et al., EPJ Web of Conferences (2017)

[8] K. Shibata, O. Iwamoto, T. Nakagawa, N. Iwamoto, A. Ichihara, S. Kunieda, S. Chiba, K. Furutaka, N. Otuka, T. Ohsawa et al., Journal of Nuclear Science and Technology (2011)

[9] Y. Gohar, D.L. Smith, Nuclear Engineering Division, Tech. rep., Argonne National Laboratory (ANL), Argonne, IL (United States) (2010)

[10] M.A. Kalugin, D.S. Oleynik, D.A. Shkarovsky, Joint International Conference on Supercomputing in Nuclear Applications p. 6012 (2014)

[11] X-5 Monte Carlo Team, Los Alamos Nuclear Laboratory (2008)

[12] M.B. Chadwick, M. Herman, P. Obložinský, M.E. Dunn, Y. Danon, A.C. Kahler, D.L. Smith, B. Pritychenko, G. Arbanas, R. Arcilla et al., Nuclear Data Sheets (2011)

[13] M.A. Kellett, O. Bersillon, R.W. Mills, Tech. rep. (2009)

[14] G. Poullot, D. Doutriaux, J. Anno, *Guide to the Expression of Uncertainties for the Evaluation of Critical Experiments* (2008)

[15] J.C. for Guides in Metrology, Tech. rep., JCGM (2008)