Fuel Evolution in Hybrid Reactor Based on Thorium Subcritical Assembly with Open Trap as Fusion Neutron Source (Computer Simulations)*)

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Results of computer simulation of the fuel evolution in thorium nuclear cycle in a subcritical assembly in case of thorium-plutonium initial composition is presented in the paper. The simulation is conducted for specialized facility in which a long solenoid with hot plasma is situated inside of the subcritical fuel assembly. The plasma column produces additional neutrons due to D-D fusion reaction that are necessary for a fission reactor with this assembly. Total intensity of neutron emission over all plasma volume with the length of 3 m is $N = 2 \times 10^{16}$ neutrons per second. We have chosen the percentage of plutonium 5% in thorium-plutonium initial composition and in this case, the effective coefficient of neutron multiplication is 0.95, as shown by our simulation. The fuel evolution was calculated for duration of operation time 3000 days. As a result, we have demonstrated the decrease in the coefficient of neutron multiplication and in the power of the nuclear fission process in the described time. Results of simulations are discussed.

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1. Introduction

Thorium power industry has a number of advantages over uranium one: no necessity to divide isotopes from natural isotope composition, minimal accumulation of radioactive waste in the course of continuous operation, practically impossible to obtain unauthorized use of fissile materials due to hard gamma radiation, unlimited supply of thorium fuel for the global energetic system. Taking into account of these advantages, a high-temperature gas-cooled reactor with thorium fuel looks very attractive for application in the energy supply system of the Russian Federation. Fuel assemblies filled by pellets with microencapsulated thorium-plutonium kernels will be used in such reactors [1]. In open fuel cycle, the operation time of such reactor will be up to 10 years. Since the novel fuel assemblies with the microencapsulated kernels were not studied in neutron-physical experiments for regimes of this reactor it is necessary to create a facility that allows carrying out such experimental studies. To solve this problem we have proposed a stand to study neutron-physical characteristics of the thorium-plutonium fuel (see [2]). In this paper, we describe results of computer simulations for the time evolution of a thorium-plutonium fuel in the stand for its long operation time. A mathematical model composed for the simulations of the process in the stand will be applied to describe the thorium fuel cycle in a hybrid reactor for power industry.

2. Stand for Studying the Evolution of Thorium-Plutonium Fuel Composition

This facility consists of a fuel subcritical assembly combined with a long magnetic trap for plasma confinement that operates as a source of fusion neutrons (see Fig. 1). The fuel assembly has a longitudinal size less than 3 m and can be situated in a cylinder of 3.5 m diameter. The magnetic trap includes an area for neutron beam injection, plasma column inside of the subcritical assemble and two units with multi-mirror magnetic field to prevent longitudinal losses of plasma energy along the axis of the plasma column. Total length of the plasma device is on the level of 12 m. Plasma parameters in the vacuum chamber of the facility is calculated taking into account the total length of magnetic trap. We use the plasma parameters in the plasma column part that is located inside the fuel assembly

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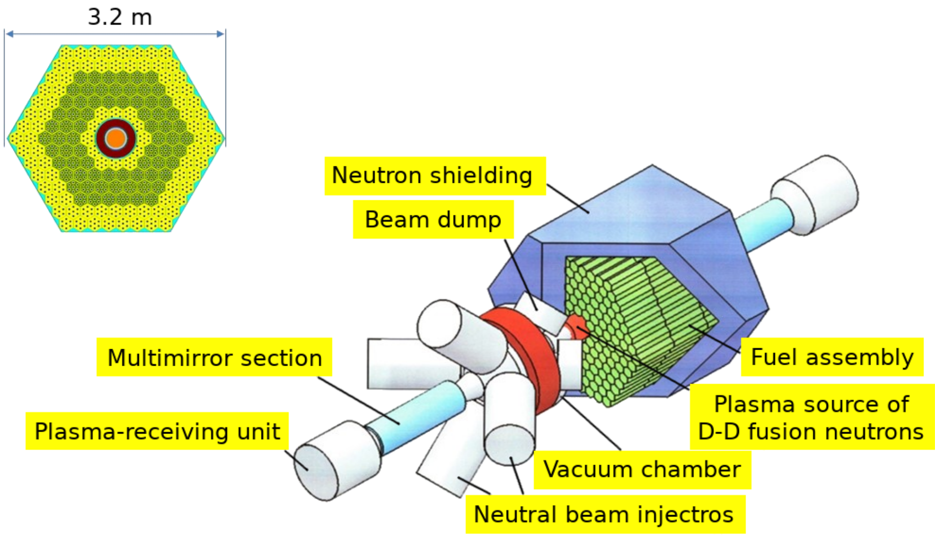

Fig. 1 Schematic of facility for studying the evolution of thorium-plutonium fuel composition.

Table 1 Parameters of plasma and atomic beams.

Diameter of the plasma column	0.3 m	Electron temperature	1.4 keV
Power of atomic beams	100 MW	Density of sloshing D-ions	$1.5 \cdot 10^{14}$ cm^{-3}
Power of beams, captured by plasma	66 MW	Average energy of sloshing ions	80 keV
Energy of neutral atoms	200 keV	Related plasma pressure, β	0.5
Warm plasma (ion) density	$2 \cdot 10^{13}$ cm^{-3}	Confinement time	0.4 ms
Warm ion temperature	0.4 keV	Neutron generation per 1 cm length	$6 \cdot 10^{13}$ n s^{-1}cm^{-1}

to calculate axial D-D neutron emission from plasma to the assembly.

3. Computer Codes and Results of Simulation

Simulation of generating 2.45-MeV thermonuclear neutrons in a long solenoid trap with heated plasma was conducted by using computer code DOL for the plasma parameters, which can be achieved at the GDMT-facility experiments [3]. The magnetic field configuration in the fuel subcritical assembly was chosen to achieve homogeneous distribution of the thermonuclear neutron emission over the assembly axis. Solved mathematical problem is composed by four main elements: (1) Fokker-Plank equation for the sloshing ions, (2) the equations of particle and energy balance for the background plasma, (3) kinetic equation for plasma interactions with injected fast atoms, (4) calculation of fusion reaction rates. The plasma parameters involved in the process simulation for the area of the neutron generation inside of the subcritical assembly is given in Table 1. A result of the simulation of neutron emission distribution over the axis of the plasma column in the solenoid is presented in Fig. 2. One can see that the neutron emission distribution is practically homogeneous

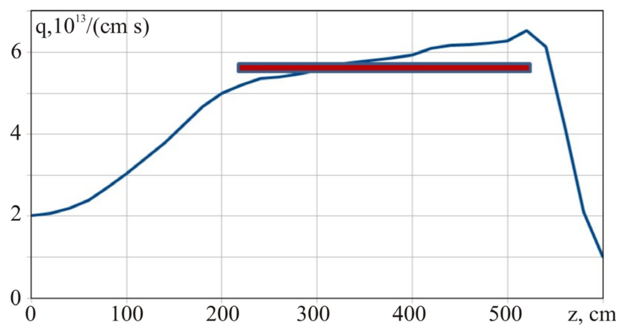

Fig. 2 Distribution of neutron emission from plasma column in the region of the subcritical assembly (the region is marked by a brown bar).

in the part of plasma column situated inside of the subcritical assembly (this part is marked by a brown bar on the plot in Fig. 2).

Total intensity of neutron emission over all plasma volume with the length of 3 m is $N = 2 \times 10^{16}$ neutron per second. After passing through a copper solenoid, the neutron emission is decreased down to level 95%. A radial flow from the solenoid into a central area of the subcritical assembly is 82% from the total emission intensity. As to loses of the neutron flux through the right and left ends of

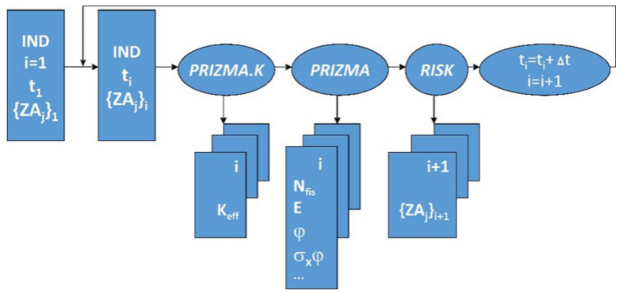

Fig. 3 Schema to realize the process of fuel evolution simulations.

the assembly, they are 9% and 4%, respectively.

The effective neutron multiplication coefficient, the neutron reproduction coefficient, the distribution of neutron fluxes and energy release are obtained in the frame of using the Monte Carlo code of PRISMA [4, 5] with continuous neutron data (ENDF/B-VII.1). Calculations of the nuclear fuel kinetics are carried out using the RISC code [6] with data on the decays from ENDF/B-VII.O and with usage of the calculation results of the fuel burnup. The fuel burnup is calculated in conjunction with the calculation of neutron transport according to the PRISMA program. In addition to the results obtained in the calculation of the PRISMA program, calculations of the burn-up coefficient of various constituents of fuel are carried out using the computer code MCU5 (ENDF/B-VII.0) [7]. The schema of the simulation process is presented in Fig. 3.

We start the calculations from the input of an initial data file (**IND**) and an initial isotope composition $\{ZA_j\}_1$. In the next step, we calculate the effective multiplication coefficient for neutrons (*k*ef) of our facility by usage of Monte Carlo code ***PRIZMA.K*** and then by usage of code ***PRIZMA*** we calculate various nuclear reaction acts (N_{fis}), an energy release (E), flows (φ), nuclei production rate ($\sigma_x\varphi$) etc. In a final stage of one computer calculation circle, we use code ***RISK*** to calculate the evolution of isotope composition in time Δt $\{ZA_j\}$ for the fuel subcritical assembly. For the second calculation circle, we use the initial data file (IND) and the isotope composition $\{ZA_j\}_2$ obtained as result of the first calculation circle. For the third circle, the results of the second calculation circle are used. And so on. We have got simulation results for dependence of the effective multiplication coefficient of neutrons (*k*ef) of our facility on a plutonium percentage in fuel composition: Pu (α), Th ($1-\alpha$). We have come to decision that optimal plutonium percentage is $\alpha = 4\%$. The value of *k*ef is 0.95 for this condition.

For geometry and parameters of a facility operated as stand to study the thorium-uranium fuel evolution, we calculated the evolution of the effective multiplication coefficient (*k*ef) and the power (P) in the case of the intensity of neutron emission 2×10^{16} n/s from the plasma source (see Fig. 4). For chosen geometry and operation parameters of

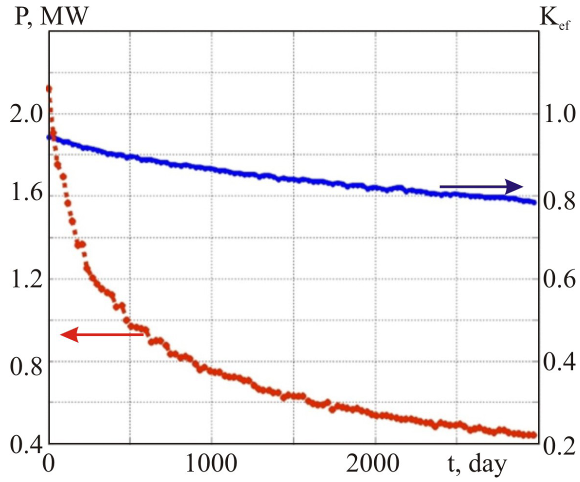

Fig. 4 Effective multiplicity coefficient (*k*ef, blue curve) and power of subcritical assembly (P, red curve) vs. operation time.

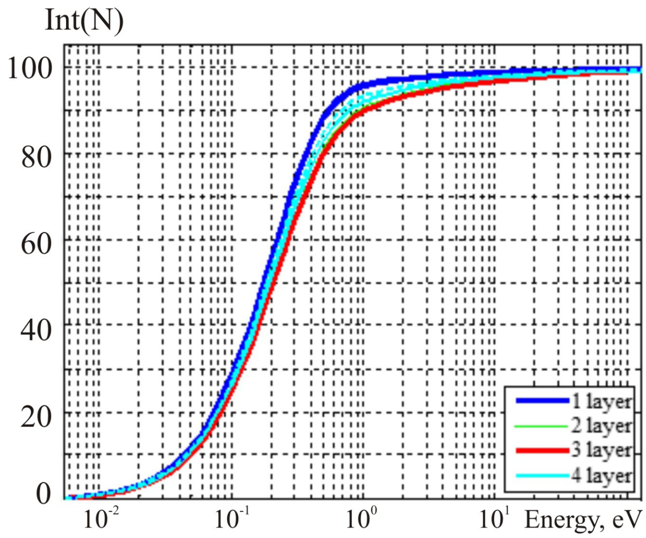

Fig. 5 Percentage of neutrons with energy less than one pointed on the axis (at the beginning of operation).

the stand one can see the monotonous decrease of *k*ef and P in operation time from levels 0.95 and 2.1 MW down to 0.8 and 0.4 MW, respectively. To prevent this decrease at these key parameters of the stand we have to increase the neutron emission level from the plasma source or to add an isotope for multiplication of the neutrons from the plasma column, systematically in the time of the stand operation. There is also possibility to input control rods for controlling the operating mode of the fuel assembly of our facility at increasing percentage of Pu in the initial fuel composition. Since nuclear reaction acts strongly depend on energy distribution of the neutrons in the local area, we control the neutron energy spectrum on all steps of computer simulations for the fuel composition evolution.

The neutron spectrum in the main part of the assem-

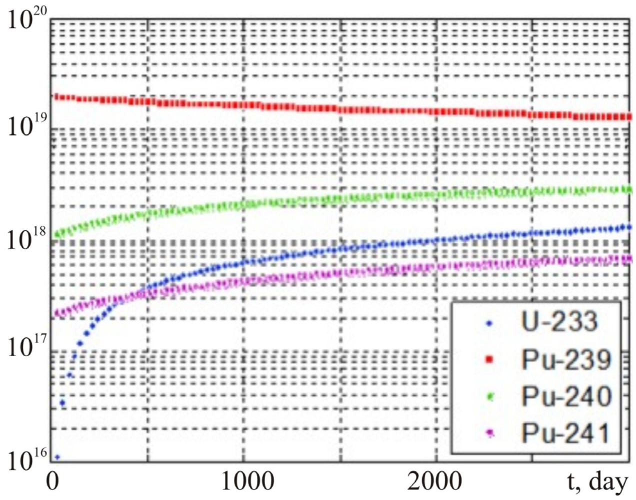

Fig. 6 Nuclear density of various isotopes in radioactive waste component in the fuel, nucl/cm^3.

bly at the beginning of the operation time is presented in Fig. 5. This plot demonstrates the percentage of neutrons with their energy less than the energy value pointed on the axis. It is seen on the plot that the number of neutrons is concentrated in the energy area less 1 eV. Such neutron spectrum is very suitable for nuclear reaction acts.

Our simulations of the facility operation in time up to 3000 days allow us to describe evolution of radioactive waste in the fuel composition. A plot in Fig. 6 presents the evolution of radioactive waste in the operation time.

One can see that minority radioactive components have their concentration at a level appropriate for using the studied nuclear fuel composition in practice application.

4. Summary and Conclusion

The computer codes to calculate the operation of the facility consisting of a fuel subcritical assembly combined with a plasma source of fusion neutrons in a long magnetic trap have been composed. These codes allow us to analyze prospect of using the thorium subcritical assembly for solving various problems. Among of these tasks:

1) Development of new and advance of existing analysis methods of relations between integral characteristics and criticality of the systems of the pulsed neutron source – subcritical fuel assembly type, methods of reactivity control by integral system characteristics.

2) Experimental study of relations between kinetic characteristics of the reactor system and its technological operating modes.

3) Experimental study of the influence of protactinium-233 accumulation and decay kinetics on the reactor system criticality in conditions of stringent criticality by the exclusive use of start-up fission nuclides at thorium core loading at the beginning of nuclear fuel campaign.

4) Experimental study of diverging fission wave spreading over the volume of subcritical assembly, co-functioning with the pulsed fast neutron source and excited by fast neutrons.

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[1] I. Shamanin, S. Bedenko *et al*., Ad. Mater. Sci. Eng. **1084**, 275 (2015).

[2] A.V. Arzhannikov, A.B. Anikeev, A.D. Beklemishev *et al*., AIP Conf. Proc. **1771**, 090004 (2016); doi: 10.1063/1.4964246

[3] D.V. Yurov, V.V. Prikhodko and Yu. A. Tsidulko, Plasma Phys. Rep. **42** (3), 210 (2016).

[4] O.V. Zatsepin, Ya.Z. Kandiev, E.A. Kashaeva *et al*., "Calculations of neutron-physical characteristics of the VVER-1000 core by the Monte Carlo method according to the PRISMA program" // VANT. Series: Physics of Nuclear Reactors **4**, 64 (2011) (in Russian).

[5] Y.Z. Kandiev, E.A. Kashaeva, K.E. Khatuntsev *et al*., Ann. Nucl. Energy **82**, 116 (2015). DOI: 10.1016/j.anucene.2014.09.0065

[6] D.G. Modestov, "Computer program RISK-2014 for solving the problems of nuclear kinetics", Preprint RFSC-ZIAPh # 243, Snezhinsk, 2014 (in Russian).

[7] D.S. Oleynik, D.A. Shkarovskiy, E.A. Gomin *et al*., "The status of MCU-5", Physics of Atomic Nuclei **75**, 1634 (2012). http://mcuproject.ru/rabout.html