Neutron data field in a fission reactor core with fusion neutron source at pulse-periodic operation

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Abstract. Results are presented on the distinctive features of the energy release dynamics in the hybrid thorium reactor operating in combination with the neutron source based on the extended magnetic mirror trap. In the reactor core configuration under study, the high-temperature plasma column is formed in a pulse-periodic mode. At a certain duty cycle (pulse ratio) of the plasma column formation, it can be expected that the fission "wave" will be formed diverging from the axial region of the system and propagating in the radial direction in the fuel assembly (blanket). Under such conditions, in order to correct the resulting offset of the energy release distribution, it is necessary to optimize the fuel composition of the assembly in order to obtain the most appropriate radial distributions of physical parameters. The studies are carried out on the basis of the full-scale model of the reactor core, in which the axial region is modified: the extended magnetic mirror trap operating as a source of fusion neutrons is installed in the reactor core axial region.

1. Introduction

In this work, the specific characteristics of spatial kinetics of the hybrid thorium reactor with the extended neutron source based on the magnetic mirror trap are studied. The "fission–fusion" reactor under study (see Fig. 1, [1, 2]) is essentially the hybrid reactor. Its reactor core, consisting of the fuel block assembly of the unified construction, is a part of high temperature gas-cooled thorium reactor HTGR [3, 4]. Other component of the hybrid reactor is the extended magnetic mirror trap installed in the near-axis region of the reactor core [5].

The extended magnetic mirror trap includes the heating region (the neutral beam injection region), the plasma column formed at the axis of the fuel block assembly and two sections with the multimirror magnetic fields installed to minimize the longitudinal plasma energy losses along the plasma column axis. The engineering design of the plasma generator of D-D (and/or D-T) fusion neutrons under consideration is based on the gas-dynamic multimirror magnetic trap [5,6] developed and currently operating in the Budker Institute of Nuclear Physics of the Russian Academy of Sciences (Siberian Branch) in Novosibirsk.
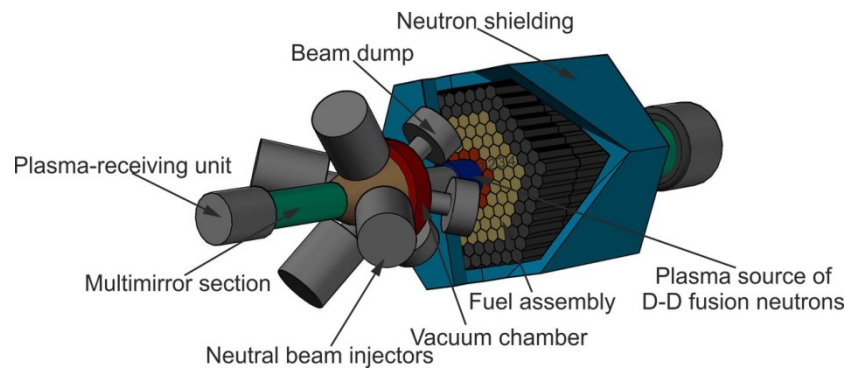
Figure 1. Conceptual design of the hybrid "fission–fusion" reactor facility.

In the hybrid reactor configuration under consideration, the high-temperature plasma column is formed in the pulse-periodic mode. At a certain duty cycle (pulse ratio) of the plasma column formation, it can be expected that the fission "wave" diverging from the axial region of the system and propagating in the fuel assembly volume will be formed. It will be induced by the pulsed source of fast D-D neutrons. Thus, under such conditions, it is important to study the fission "wave" propagation in the assembly volume and the consequent formation of the resulting energy release distribution. These studies contribute to optimizing the system reactive components and correcting the revealed offsets of the radial and axial energy release distributions in the fuel volume. From the point of view of applied problems, the results of this work will contribute to providing the steady state operation of hybrid systems controlled by the external pulse-periodic source of additional neutrons.

2. Materials and methods

2.1. Computational model

To study the fission "wave" propagation, the detailed 3D-model of the facility (see Fig. 1) was simplified to the two-layer cylinder with the plasma D-D neutron generator installed in its central region (see Fig. 2). The computational model used in simulations is as follows: the cylindrically-symmetric system is infinite along the 0Z axis (see Fig. 3). The system consists of three regions bounded by the radii of 30, 118.34 and 154.7 cm. The height of the system is 100 cm, and the white boundary is assumed at its ends. There is the pulse-periodic source of D-D neutrons (GDT-FNS) in the inner region of the model system, and, in the outer region, there is the graphite reflector with a density of 2.2 g/cm^3. The reactor core, consisting of 50 equal-volume layers and containing homogenized Th$_{(1-\alpha)}$Pu$_\alpha$ fuel, is between these regions. The initial nuclear composition of the homogenized region is presented in Table 1.
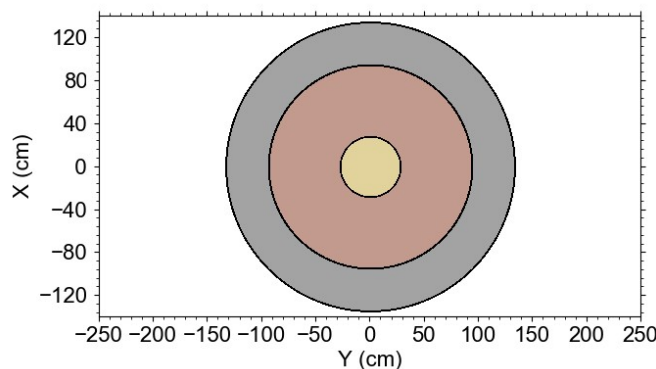
Figure 2. Model of the reactor cross-section used in simulations (XY plane).
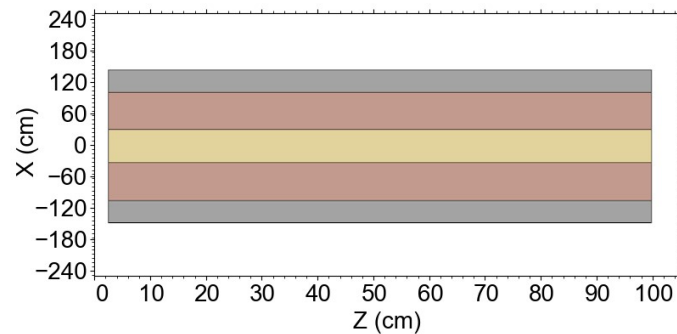
Figure 3. Model of the reactor longitudinal section used in simulations (XZ plane).

Table 1. Composition of the homogenized fuel in the facility blanket.

| Nuclide	Nuclide density [nuclides/(b·cm)]
^{232}Th	6.57E-05
^{239}Pu	6.18E-05
^{240}Pu	3.29E-06
^{241}Pu	6.60E-07
^{16}O	2.63E-04
^{12}C	9.35E-02
Si	1.36E-03
Ti	3.41E-04
He	2.53E-05

2.2. Methods for numerical studies

Simulations of the stationary neutron characteristics and space-time distributions of the fission "wave" were performed using the PRIZMA software package with the ENDF/B-VII.I system of constants [7], developed in the Zababakhin All-Russia Research Institute of Technical Physics (Russian Federal Nuclear Center). To determine the stationary neutron characteristics ($k_{eff}(\alpha)$, where α is the mass percentage of Pu atoms in the fuel composition), the conditional critical simulation problem was solved. The dynamics of the fission "wave" distribution was studied by means of performing statistic simulations of the neutron transport from an isotropic source located at the central axis of the facility. The neutron flux intensity was 1 ($n \times s^{-1}$), and the neutron energy was 2.45 MeV. The results obtained for 50 equal-volume layers between the radii of 30 and 154.7 cm are presented in the next section.

3. Results

3.1. Results of stationary neutron characteristic simulations

The simulation results of the stationary neutron characteristics of the reactor core with the additional D-D source are presented in Fig. 4 and Table 2.
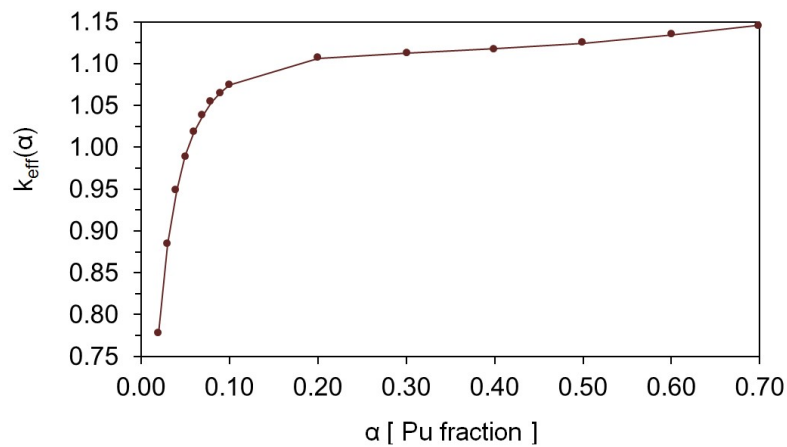
Figure 4. Effective neutron multiplication factor of the facility as a function of mass percentage of plutonium in the fuel composition $Pu_{(\alpha)}$, $Th_{(1-\alpha)}$.

From Fig. 4 and Table 2, it is seen that, for the chosen Th-Pu fuel composition (the mass percentage of plutonium is $\alpha = 4\%$), the effective neutron multiplication factor is $k_{eff} = 0.95$ [8, 9], which is required for the hybrid systems.

**Table 2.** Stationary neutron characteristics of the simulated system.

^{232}Th [wt.%]	Pu [wt.%]	Nuclide density [nuclides/(b·cm)]				
		^{232}Th	^{239}Pu	^{240}Pu	^{241}Pu	k_{eff}
96	4	1.90E-05	1.10E-06	2.10E-07	5.09E-04	0.9460

*3.2. Results of the facility space-time characteristic simulations.*

Results of the facility space-time characteristic simulations (for the fuel composition presented in Table 2) at time of its start-up with "cold" reactor core are presented in Fig. 5. From Fig. 5, it can be seen that the neutron source operating in pulse-periodic mode affects only the layers adjacent to the source, and its effect vanishes within 0.01 ms when neutrons reach the 2-nd row of graphite fuel blocks of the facility blanket. The simulation results showed that the further progress in optimizing the hybrid reactor under consideration (calculations of $k_{eff}(t)$ and other necessary neutron characteristics) can be achieved by using in the model the continuously operating stationary neutron source instead of the pulsed-periodic one (with pulse duration of 1 ms and the pulse ratio (duty cycle) equal to 2).

In the case of long-term irradiation, the results of $k_{eff}(t)$ calculations are presented in Fig. 6.

The results presented in Fig. 6 show: (1) The chosen fuel composition can provide the long-term facility operation. (2) To maintain constant values of $k_{eff}(t)$ and $P_{th}(W)$, the D-D source should permanently feed the reactor core with neutrons, and, in this case, the neutron production rate should permanently increase (see Fig. 7) during the entire fuel campaign.
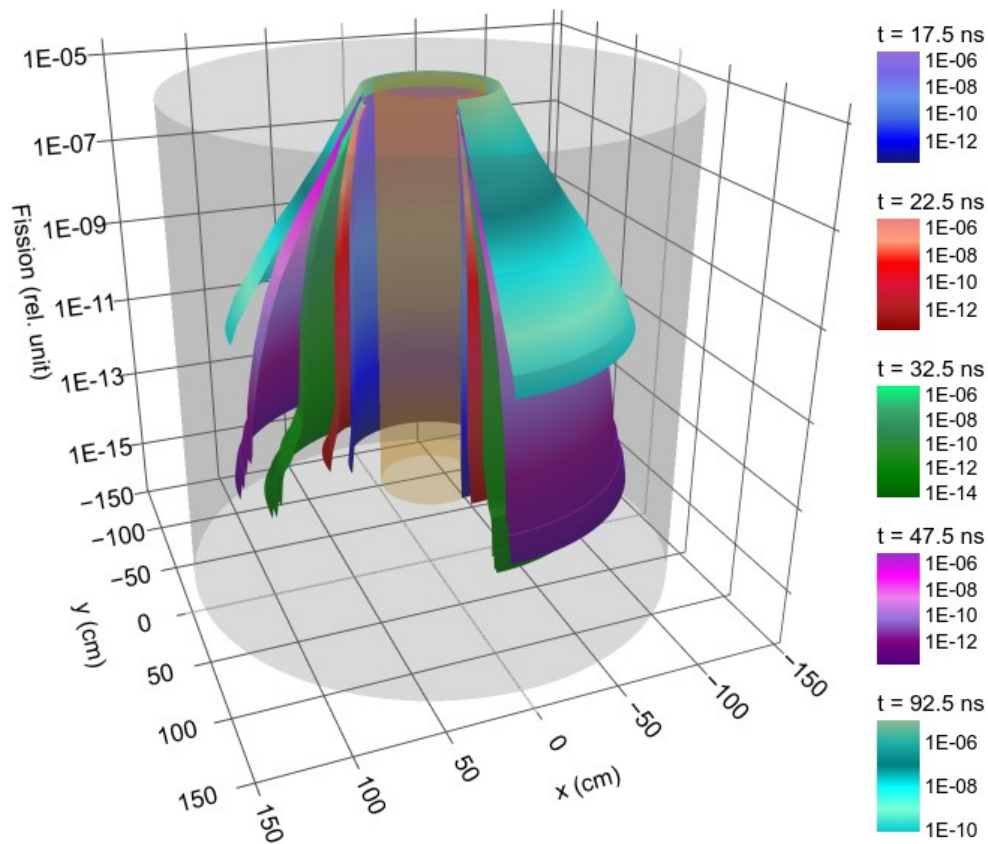
Figure 5. Dynamics of energy release in "fission–fusion" hybrid facility.
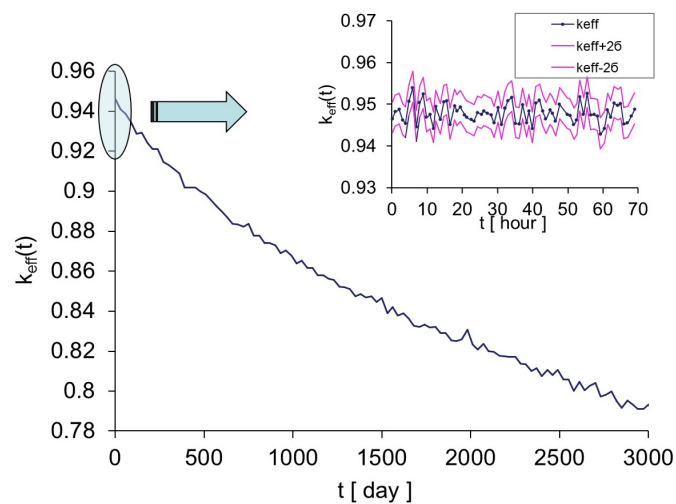
Figure 6. Time dependence of effective neutron multiplication factor.
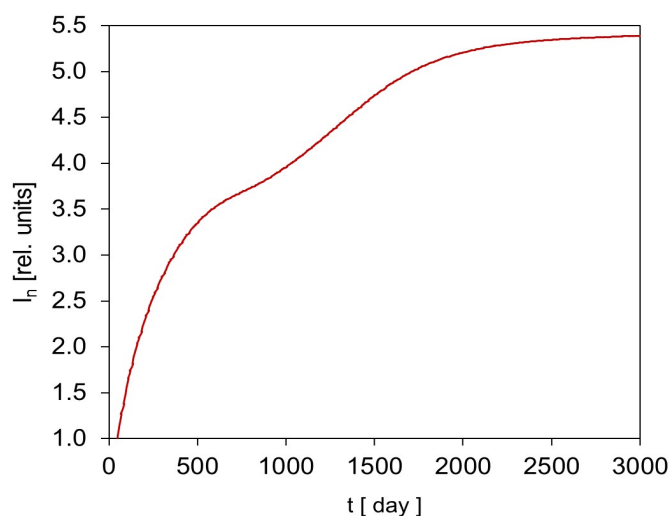
Figure 7. Neutron production rate per volume unit as a function of the operation time of the facility fuel assembly.

4. Conclusions

(i) The GDT-FNS neutron source operating in pulse periodic mode affects only the blanket layers adjacent to the source, and its effect vanishes within 0.01 ms when neutrons reach the 2-nd row of graphite fuel blocks of the facility blanket.

(ii) At time of the facility start-up with "cold" blanket, the GDT-FNS should provide stable intensity of D-D neutrons generation in the range from 10^{16} to 2×10^{18} neutrons per second in the entire plasma column.

(iii) When the pulse duration is 1 ms and pulse ratio is equal to 2, the GDT-FNS operating in the required range of D-D neutron generation intensity will provide the blanket heating rate of 10 ($K \times h^{-1}$), that meets the requirements for the thermal technical engineering reliability during the cold start-up.

(iv) To maintain the constant multiplication factor $k_{eff}(t)$, the GDT-FNS should permanently feed the reactor core with additional neutrons, while the D-D neutron production rate should permanently increase during the entire fuel campaign.

(v) It can be stated that the results obtained confirmed the possibility of using the PRIZMA software package developed in the Zababakhin All-Russia Research Institute of Technical Physics for the full-scale simulations of neutron characteristics of hybrid facility in different modes of the fusion neutron plasma source operation.

Acknowledgments

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