Subcritical Assembly with Thermonuclear Neutron Source as Device for Studies of Neutron-physical Characteristics of Thorium Fuel

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Abstract. A device for studies of neutron-physical characteristics of thorium fuel is described in this paper. The device consists of a thorium subcritical assembly combined with a source of fast neutrons. A long magnetic trap with injection of high energy neutral atoms into a plasma column serves as a source of thermonuclear neutrons. The subcritical assembly design consists of Fuel Block of the Unified Design. The analysis of the requirements for the plasma as the neutron source is presented in the paper.

INTRODUCTION

Thorium-uranium power industry has a number of advantages over uranium-plutonium one: it has an unlimited supply of fuel to the Globe; natural thorium consists of a single isotope and its involvement in fuel cycle unlike uranium does not require time consuming separation of isotopes; Uranium-233, derived from thorium, is the most attractive of the three elements: U-235, of Pu-239 and the U-233, at least in terms of neutron physics; Uranium-233 can be used as a fuel suitable for almost any type of fission reactor; there is minimal accumulation of radioactive waste in the course of the continuous operation of the thorium-uranium reactor; practically impossible unauthorized use of fissile materials due to hard gamma radiation. Taking into account of these advantages, a high-temperature gas-cooled reactor with thorium fuel looks very attractive for application in Russian Federation. Fuel assemblies filled by pellets with microencapsulated thorium-uranium kernels should be used in such reactors. 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. These experimental studies should be devoted to several topics. The multiplying properties of nuclear fuel compositions based on thorium and the spatial distribution of neutron fluxes in the fuel assemblies and fuel blocks are among of them.

In this paper we have proposed that such facility must consist of a thorium subcritical assembly combined with a source of fast neutrons. On our opinion a long magnetic trap with injection of high energy neutral atoms into a plasma column will be most appropriate as a source of 14-MeV thermonuclear neutrons. The overall structure of the device combining the fusion neutron source with the thorium subcritical assembly is described in the paper. Analysis of the requirements for the plasma as the neutron source is given and key peculiarities of the engineering solution on plasma heating and confinement in the device are also discussed in the paper.

OVERALL STRUCTURE OF THE DEVICE

The source of fast neutrons has to be placed in to the central area of the fuel-containing part of a reactor core composed by a hexagon graphite fuel blocks. The cross section of the fuel-containing part of the reactor core is presented in Fig. 1. Detail description of this reactor core was given in Ref. 1. The fuel assemblies are shown by gray hexagons in left part of the Fig. 1. There are two types of fuel assemblies in the arrangement scheme of the thorium subcritical assembly. These types are marked by the figures 1 and 2 in the right side of Fig.1. They have two different isotope compositions of Plutonium which described in Table 1. The fuel-containing part of the reactor core is covered by two layers of hexagon block of pure graphite (white hexagons in Fig. 1). The top and bottom of the reactor core having 2.4 m height are covered by graphite of 0.3 m thick.

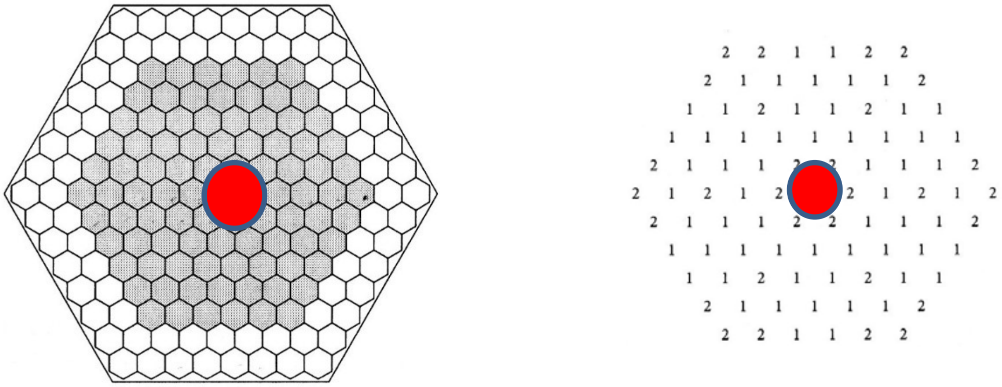

FIGURE 1. Arrangement scheme of the first and second types fuel assemblies in a small reactor core

Fuel Assembly (Fuel Block of the Unified Construction [2]) is a hexagon graphite fuel block with the width across the flats of 0.2 m and height of 0.8 m. There are 78 holes with the diameter of 8.2 10^{-3} m for FPs of 0500 and/or 1000 type and 7 holes with the diameter of 2.4 10^{-2} m for passing gaseous coolant (helium) (see [1]).

Table 1.

Pu isotopes	Pu-238 (%)	Pu-239 (%)	Pu-240 (%)	Pu-241 (%)	Pu-242 (%)
Type 1	1.8	59	23	12.2	4
Type 2	0	94	5	1	0

The source of fast neutrons is drawn as a red circle in the central part of the arrangement scheme of the reactor core (see Fig. 1). One can see that this circle occupies of the places of seven samples with the Type 2 isotope composition. These seven samples have to be replaced by a device in which a magnetic field system containing a vacuum chamber with fusion plasma. A schematic drawing of the device is presented in Fig.1. The device consists of a magnetic trap with injection of high energy neutral atoms into plasma for plasma heating in a local area of a plasma column (left side of the picture) and of a long solenoid with heated plasma in a vacuum chamber placed in the thorium subcritical assembly. The main idea of this plasma device is based on a Gas-Dynamic Multi-mirror Trap (GDMT) that is currently being developed in the Budker Institute [2]. The stated goals of the GDMT project include containing deuterium plasma with hot sloshing ions with the electron temperature up to 1 keV and the density of 10^{20} m^{-3} in discharges at least 1s long. This would provide the effective Q_{DT} ~0.1 [3]. There are variations of the GDMT design, such as the diamagnetic confinement [4] and the helical mirrors [5], which can significantly improve the energy efficiency.

In order to install the neutron plasma source inside of the subcritical assembly the outer radius of the solenoid for generating the longitudinal magnetic field must be less than 60 cm. Plasma radius has to be 15 cm. Total length of the device is estimated on the level 10 meters. Main part of the magnetic coils of this device is planned as superconducting system.

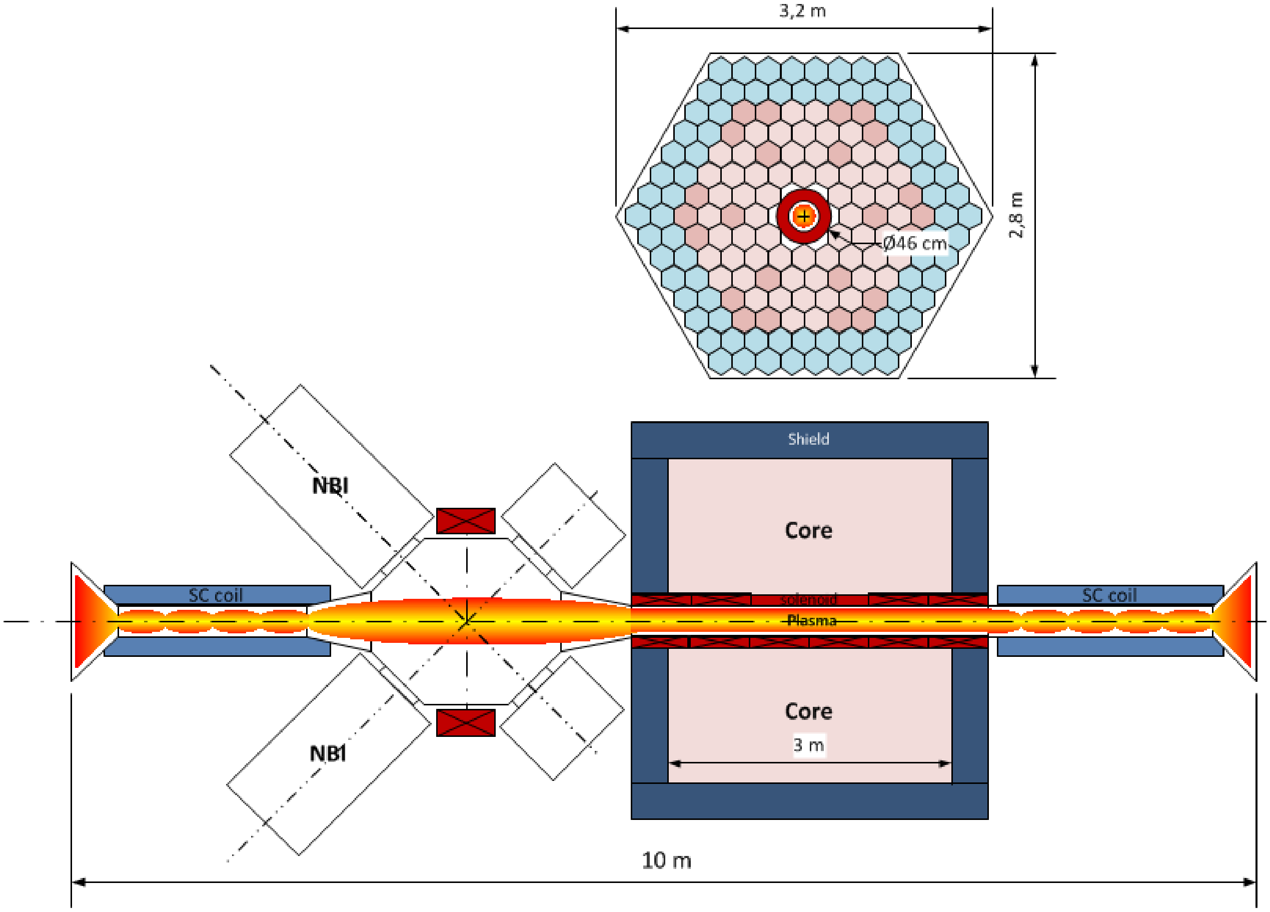

FIGURE 2. A schematic drawing of the device for testing the thorium subcritical assembly

Geometrical sizes of the device units and estimation of the main technical parameters are given in Table 2. It has to be pointed out that the total power of the beam injection system must be chosen with taking into account the neutron multiplication factor of the fuel assembly. In case of the deep subcritical assembly, when the effective multiplication factor has a value less than k_{ef}~0.50 that the injection power of the deuterium beams has to be 100 MW. In opposite case when k_{ef}=0.95, 20 MW injection power may be enough for achieving necessary density of neutron fluxes in the test area of the thorium subcritical assembly.

Table 2.

Length of the plasma column in the section to generate fusion neutrons	3 m
Outer radius of the solenoid inside of the subcritical assembly	0.6 m
Inner diameter of the vacuum chamber in the section to generate fusion neutrons	0.35 m
Magnetic field in the section to generate fusion neutrons	2-3.5 T
Length of the plasma chamber for neutral beam injection	2 m
Particle energy of the injected beams	200 keV
Total power of the beam injection	100 MW (kef=~0.50) 20 MW (kef=0.95)
Magnetic field in the section for neutral beam injection	0.7 -1 T
Length of the multimirror sections	2.5 m
Magnetic field in the multimirror section (min/max)	4.5 / 9 T

Calculation model of subcritical assembly was created by using the program code of MCU-5 series [6]. Geometrical module of MCU-5 code allows simulating 3D systems with different complexity geometry using combinatorial approach based on description of complicated systems by combinations of elementary bodies and surfaces. This model will be applied to analyze the describe geometry of the device in detail.

FUSION PLASMA PARAMETERS

On basis of the presented technical parameters one can calculate the parameters of the plasma and sloshing ions in the device. For the case of the gas-dynamic trap such computer simulations have been already done by utilizing the computer code described in Ref. [7]. Results of this simulation for searching the optimal plasma conditions at the neutral beam injection with 100 MW power is presented in Table 3.

Table 3.

Diameter of the plasma column in the section to generate fusion neutrons	0.3 m
Warm plasma (ion) density in the section to generate fusion neutrons	$4\ 10^{13}$ cm^{-3}
Ion temperature of the plasma in the section to generate fusion neutrons	0.4 keV
Electron temperature of the plasma in the section to generate fusion neutrons	1.4 keV
Density of sloshing D-ions	$4\ 10^{13}$ cm^{-3}
Average energy of sloshing ions	80 keV
Related plasma pressure, β	0.5
Confinement time	0.4 ms
Neutron flux in the section to generate fusion neutrons	$0.9\ 10^{13}$ $n\ s^{-1}\ cm^{-2}$

The goal of the next step of this research work is to provide detail computer simulations for the geometry and parameters of the device for testing the thorium subcritical assembly described above. Research work provided on this device will give scientific information for supplement of the evaluated nuclear database in design of compact gas-cooled thorium reactor.

ACKNOWLEDGMENTS

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REFERENCES

[1]. I. Shamanin, S. Bedenko, et al. “Gas-Cooled Thorium Reactor with Fuel Block of the Unified Design”, Advances in Materials Science and Engineering, vol. 1084, pp. 275–279 (2015).

[2]. A. Beklemishev, A. Anikeev, et al., “Novosibirsk Project of Gas-dynamic Multiple-Mirror Trap”, Fusion Science and Technology 63(1T), p.46 (2013).

[3]. A.V. Arzhannikov, A.V. Anikeev, A. D. Beklemishev et al., “Gas-dynamic trap with Q~0.1 as a driver for hybrid thorium reactor”, Conference Program of the OS2014, www.os2014.org, **OS5-04.**

[4]. A. D. Beklemishev, Physics of Plasmas, **23**, 082506 (2016).

[5]. V. V. Postupaev, A. V. Sudnikov, A. D. Beklemishev, I. A. Ivanov, Fusion Eng. and Design, **106**, 29 (2016).

[6]. D.S. Oleynik, D.A. Shkarovskiy, E.A. Gomin, and et al., “The status of MCU-5”, Physics of Atomic Nuclei, **75**, 1634−1646 (2012).

[7]. D. V. Yurov, V. V. Prikhodko, and Yu. A. Tsidulko, “Nonstationary model of an axisymmetric mirror trap with nonequilibrium plasma”, Plasma Physics Reports 42 (3), 210-225 (2016)