Neutron-physical studies of ceramic fuel of a high-temperature reactor in the regime of long-term operation

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Abstract: In this paper, we present the results of studies of the physics of a high-temperature gas-cooled thorium reactor facility of low power operating in the long-term operation mode. Carried out a comparative neutron-physical calculation of promising fuel compounds ((Th,Pu)O₂, (Th,Pu)N, (Th,Pu)C), which can be included (dispersed) into the matrix of the fuel compact of the reactor under investigation. It has been established that the use of (Th, Pu) C-fuel will increase the burn-up of heavy metal by 5%, reduce the accumulation of fission products and CO, increase the service life of fuel.

1. Introduction
To date, the world economy needs modern, autonomous, reliable and environmentally safe energy sources, such energy sources are nuclear low-power innovative systems [1]. A number of designs and detailed projects are presented in this area of development of nuclear technologies, of which the most promising are the projects of high-temperature gas-cooled reactors (HTGR) with thorium fuel [1-8]. These reactors have the property of transportability, 100% factory manufacturing, short installation time and the ability to work for a long time without overloading. It is these low-power reactors brought to commercial and competitive level that can form the basis of regional energy in Russia and some other countries. A topical issue is the search for new types of structural materials and promising fuels that can be under the influence of neutron radiation for a long time without significant changes in their structure. The direction, which can also be attributed to innovative research, is related to the prospect of using dispersion-type fuel in the epithermal spectrum of HTGR [9, 10]. Despite the fact that this subject has been studied since the 1970s and many investigations have been carried out in this direction recently, works devoted to dispersion fuel are being actively pursued today. Promising fuel compounds (microfuel) that can be included (dispersed) in the matrix of the HTGR fuel compact are the following types: (Th,U)O₂, (Th,Pu)O₂, (Th,U,Pu)O₂, (Th,U)C, (Th,Pu)C, (Th,U Pu)C, (Th,U)N, (Th,Pu)N, (Th,U,Pu)N.

In the present work are studied fuel ceramic compounds (Th,Pu)O₂, (Th,Pu)N, (Th,Pu)C, which have proven themselves in reactor plants operating in the thermal and epithermal neutron spectrum. This study focuses on finding the composition of microfuel and the fuel compact matrix which for a long time can work in the spectrum of a high-temperature gas-cooled thorium reactor units (HGTRU, Russia, Tomsk) [7,8]. The peculiarity of HGTRU [7] is that this reactor unit is capable of producing heat, electricity and hydrogen. It is possible to modify the active zone of reactor in the framework of...
the concept proposed by the staff of the Institute of Nuclear Physics of the Siberian Branch of the Russian Academy of Sciences (Russia, Novosibirsk) [11].

2 Calculation part

2.1 Calculation model
To analyze the effective use of fuel ceramic compounds (Th, Pu)O$_2$, (Th, Pu)N, (Th, Pu)C in the HGTRU [7, 8], a computational 3D model of the reactor cell was created. 3D model was created in the program MCU5 [12]. MCU5 code is intended for simulating the processes of neutron, photon, electron and positron transport by analog and weight Monte Carlo methods [12]. When performing neutron-physical studies, the results was taken into account performed studies of neutron reactions on Th nuclei [13, 14].

The main parameters of the reactor, used when creating the input file, are presented in Table 1 [7, 8].

| Parameters active zone of reactor |       |
|----------------------------------|-------|
| Power, MWth                      | 60    |
| Service life, year               | to 50 |
| Diameter of active zone of reactor with reflector, m | 4.0 |
| Height of active zone of reactor with reflector, m | 3.0 |
| Height of the active zone of reactor, m | 2.4 |
| Number of fuel blocks, pieces    | 381   |
| Number of fuel channels in 1 assembly, pieces | 76 |

| The parameters of the fuel cell |       |
|--------------------------------|-------|
| Diameter of the fuel pellet, mm | 12    |
| Height of fuel pellet, mm       | 20    |
| The thickness of the protective coating of SiC, μm | 300 |
| The thickness of the layer is PyC, μm | 90  |
| Thickness of Ti$_3$SiC$_2$, μm | 35    |

In calculation, the temperature of all materials in the core is assumed to be 300°K. The evaluation of the neutron-physical parameters of the fuel compounds under study was carried out for a "cold" reactor. Coatings for microfuel are made of materials whose cross sections do not have significant resonant peaks, therefore, to simplify the calculations, the method of partial homogenization [15]. In this approximation, the fuel core coatings are homogenized together with a graphite matrix. A similar method of partial homogenization was used by the authors in [15, 16].

2.2 Neutron physics research
The neutron-physical calculation of the investigated fuel compounds is performed for different values $\omega_f$ ($\omega_f = N*V_{\text{microfuel}}/V_{\text{matrix}} = V_{\text{fuel}}/V_{\text{matrix}}$).

Figure 1 shows the results of calculation of the dependence of $\chi(\omega_f)$ for Th. An analysis of the dependence of $\chi(\omega_f)$ in the HGTRU cell showed that the efficiency of the use of thorium (burnup) $\chi$(Th) is higher when using the (Th, Pu)C-compound for all the values of $\omega_f$. The maximum value of $\chi$ is reached for $\omega_f$ in the range from 9 to 19% (Figure 1). Figure 2 shows an analogous dependence of $\chi(\omega_f)$ for Pu$^{239}$. The maximum burnup of Pu$^{239}$ (~96%) is achieved for $\omega_f = 6$–7% in the range from 5 to 17%. For $\omega_f > 17$ % (Th, Pu)O$_2$- compound shows the best result. The use of (Th, Pu)N- compounds is expedient, but for $\omega_f$ in the range from 5 to 13%.
Below, in Figure 3, the dependence $k_{\text{eff}}(\omega_f)$ is illustrated. The maximum multiplication factor ($k_{\text{eff}}$) is achieved when using $(\text{Th},\text{Pu})O_2$ compound, $k_{\text{eff}}(5\%) = 1.49$ (Figure 3). However, a low value of $-(k_{\text{eff}}^{-1})/k_{\text{eff}}$ does not require a large number of rods to compensate for excessive reactivity. From this point of view, the best option for organizing a stable reactor operation without fuel recharge is $(\text{Th},\text{Pu})N$- or $(\text{Th},\text{Pu})C$- compounds. Excess reactivity can be further compensated for by Pu$_{239}$ [7] or Pa$_{231}$ [17].

3. Conclusion
This paper presents the results of studies of the physics of a high-temperature gas-cooled thorium reactor installation using promising fuel compounds ($(\text{Th},\text{Pu})O_2$, $(\text{Th},\text{Pu})N$, $(\text{Th},\text{Pu})C$). The computational 3D-model is developed using the code of programs of the MCU5 series. It has been established that the use of (Th, Pu) C-fuel will increase the burn-up of heavy metal by 5%, reduce the accumulation of fission products and CO, increase the service life of fuel. The use of (Th,Pu)C-fuel does not require a large number of rods to compensate for excessive reactivity.

For the HTGRU reactor plant used as a fuel (Th, Pu) C-compound, there is more flexibility in relation to fuel cycles, which creates the potential to easily adapt the reactor to changes in the economic situation in the market.
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