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Gas-cooled thorium reactor with fuel block of the unified design

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Abstract

Scientific investigation aimed at the implementation of advance technological platform is carried out in Russia based on the ideas of nuclear fuel breeding within closed fuel cycle and on the physical principles of fast reactors. Innovation design of low-power reactor facilities also fall under the new technological platform. High-temperature gas-cooled nuclear reactors operated with thorium fuel load possessing advantageous features of transportability, factory prefabricated manufacturing, short on-site assembly and start-up period and ability to work during extended time periods without fuel reloading represent promising direction of development in this area of nuclear power generation. It is specifically this type of low-power nuclear reactors brought to commercially competitive level that must form the basis of regional power generation in Russia. The objective of the present study is to develop the concept of low-power inherently safe thorium-fueled nuclear power installation based on the unified design of the fuel block.

Scientific research and numerical experiments were performed using verified computer codes of the MCU-5 series, advanced libraries of evaluated nuclear data (ENDF/B-VII.0, JEFF-3.1.1, JENDL-4.0, ROSFOND, BROND, BNAB and others) and multi-group approximations.

Analysis of information materials pertaining to the use of thorium as fuel element in rector facilities of the new generation and of its future potential was performed in the present study. Results of the first phase of neutronics studies of 3D model of high-temperatures gas-cooled reactor facility on the basis of unified design of the fuel block are presented. Calculation 3D model was developed using the software code of the MCU-5 series. Several optimal configurations of the reactor core were selected according to the results of comparison of neutronics characteristics of the examined options for the purpose of development of small-size modular nuclear power installations with power up to 60 MW. Results of calculations of reactivity margin of the reactor, neutron flux distribution and power density profiles are presented for the selected options of reactor core configuration.

Keywords: Thorium; Gas-cooled nuclear reactor; Unified design of the fuel block; 3D calculation model.

Current status of research

Currently many countries adopt programs of development of nuclear power generation. Federal Target Program "Nuclear Technologies of New Generation for the Period of 2010–2015 and for the Future Period until 2020" was adopted in Russia. New technological platform incorporating closed nuclear fuel cycle (NFC) and fast nuclear reactor technologies constitutes the basis of the above program.

Research efforts aimed at the development of nuclear technologies capable to ensure full-scale involvement of natural uranium and thorium in the nuclear fuel cycle fall under the new technological platform. First of all this refers to the technologies of closed nuclear fuel cycle and fast reactors (reactors of the BN-600, BN-800 and BN-1200 types), as well as to the innovation projects of prospective types of nuclear reactor facilities and low-power (10–100 MW) nuclear power installations (NPI).

A whole spectrum of developments in the field of low-power NPIs was presented during recent years. The most thoroughly developed designs include small-size modular sodium-cooled fast reactor developed by Toshiba Company from

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Japan, and the ARC-100 project promoted on the market by the Advanced Reactor Concepts Company from the U.S.

Pilot demonstration unit BREST-300-OD [1,2] planned to be commissioned at the Open Joint Stock Company "Siberian Chemical Combine" by the year 2020 which is expected to become the new link within the promising model of closed nuclear fuel cycle in Russia refers to the thoroughly enough developed and finalized concepts of fast reactors with power levels falling under the category of low-power NPIs.

Another direction of development within the niche of low-power modular reactors is represented by high-temperature and superhigh-temperature NPIs. A whole number of reactor designs and projects elaborated in details with temperatures within the approximate range from 900 °C to 1200 °C are presented along this direction of reactor development, among which the high-temperature gas-cooled reactors (HTGR) [3–9] are the most promising. HTGR technology due to its unique properties as pertains to safety and environmental friendliness is capable to ensure complex electricity and heat power supply and to resolve, in particular, the outstanding problem of financially efficient hydrogen production [4,7,9].

It is clear that low-power NPsI are not a new original idea, but, nevertheless, the design projects for their development on the basis of reactor facilities with thorium-based fuel compositions represent a promising direction in nuclear power generation. Besides the above the market of low-power thorium-loaded NPIs can become the potentially favorable and priority direction in the regional power generation in Russia.

The purpose of the present study is to develop the concept of inherently safe low-power thorium-loaded NPI on the basis of fuel block with unified design.

Implementation of the concept implies that it will be realized taking into consideration all new knowledge obtained in the field of reactor development and construction and in neutron physics. Working out the concept will allow initiating the complex of studies the final result of which will be the development of the design of high-temperature gas-cooled thorium-loaded reactor installation (HTGRI) and its subsequent market promotion.

Analysis of information materials on the use of thorium as the nuclear fuel element of nuclear power installations

Analysis of available calculation and experimental information (Evaluated Nuclear Structure Data File (ANDSF), Experimental Nuclear Reaction Data (EXFOR)) on the resonance absorption of neutrons by thorium and uranium nuclei allowed making the conclusion on the existence of the following important feature. Two powerful enough resonances in the energy dependence of absorption cross-section with amplitudes of about 11,000 barns and 8000 barns are observed in the interactions of neutrons with ^{238}U nuclei within the interval of neutron energies from 4 eV to 30 eV. Resonance (about 300 barns) is present as well in the interactions of neutrons with ^{232}Th nuclei within the same energy interval, but, however, this amplitude is negligibly small as compared with resonances in the case of ^{238}U. This feature allowed explaining the following important fact discovered by us in the numerical experiments. This fact is as follows: when fertile ^{238}U is replaced with fertile ^{232}Th in the oxide fuel composition $(U,Pu)O_2$ optimal value of the ratio of the volume of water (moderator) to the volume of fuel is significantly increased (by up to five times) in the multiplying system consisting of fuel rods (fuel pins) with diameters up to 12 mm. Numerical experiments were performed at the Institute for Safety Research and Reactor Technologies of the Forschungszentrum Juelich research center (Juelich, Germany, 1998–1999). Physics of light-water reactor facility of VVER type operated with long and super-long residence times of fuel compositions on the basis of thorium, high-enrichment uranium and plutonium in the reactor core (up to 10 years) was investigated in the studies in question [10].

One more feature (anomaly) associated with dependence of resonance absorption on the ratio of moderator volume to the fuel volume in the multiplying thorium-containing system $\{(m\%U,n\%Th)O_2,\ (m\%Pu,n\%Th)O_2\}$ operated with thermal neutron spectrum was discovered in the course of subsequent numerical studies [11,12] and experiments (the studies were performed on the basis of IRT-T research nuclear reactor, unique identification code of the studies is RFMEFI59114 × 0001). The anomaly amounts to the following: sharp increase of resonance neutron absorption is observed within certain interval of variation of the ratio of moderator volume to fuel volume (V_{mod}/V_{fuel}) with fixed value of characteristic dimensions of the nuclear reactor fuel rod. Within this interval resonance absorption for uranium fuel system is by three and more times larger than that for thorium system. Numerical experiments were performed for multiplying systems with light water and graphite moderator. This anomaly is the most clearly manifested in the case of graphite with characteristic sizes of the fuel kernel equal to 300 – 400 μm [4,11–13].

Significantly smaller resonance absorption in the case when ^{232}Th serves as the fertile nuclide explains the following two important advantages. The first advantage is that the strong block-effect in the distribution of epithermal neutron flux over the volume of the fuel kernel resulting in the absorption of slowing down neutrons within relatively thin peripheral layers is significantly weaker in the thorium system. As the result, integral number of fissions within nuclear fuel element increases with its sizes remaining constant. This ensures significant increase of efficiency of use of fuel due, in particular, to the increased duration of fuel residence in the core. The second advantage is the significantly larger quantity of moderator in the thorium system. This ensures significant increase of thermal inertia with additional advantages pertaining to enhanced safety and reliability associated with it [4,8,10,13–15].

Numerical studies and experiments were performed for fuel compositions in which plutonium or uranium with high ^{235}U enrichment acted as the fuse for the starting load of the NPI core, i.e. physics of fuel composition and of the NPI within the NFC of new generation was investigated. In particular, in the case of $(m\%Pu,n\%Th)O_2$ composition