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Neutronic properties of high-temperature gas-cooled reactors with thorium fuel

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ABSTRACT

High-temperature gas-cooled low-power thorium reactor units (RU) serve as ideal sources of heat energy for supply to remote areas, large naval bases and military garrisons. This study is focused on neutronic characteristics of a 60-MWth low-power thorium reactor core with fuel blocks and pellets of different configurations. The optimal configuration was selected from these combinations and enabled the reactor to operate for a minimum of 3000 days at a capacity of 60 MWth. Additionally, this study investigated the use of burnable absorber ZrB_2 sprayed onto the lateral surface of the fuel pellets in the reactor to reduce the initial excess reactivity.

1. Introduction

Existing nuclear energy technology in Russia uses thermal light-water reactors (LWR), which have certain disadvantages. Additionally, scientific, technical, economic and environmental considerations render the fabrication of a large-scale, balanced nuclear energy system based on this platform impossible. These reactors possess two major drawbacks: the low U use efficiency and the formation of a large number of minor actinides (e.g. Am, Cm and Cf) that must be dealt with during the uranium–plutonium fuel cycle stages. Ongoing exploratory research projects concerning the implementation of a new technological platform are based on the expanded reproduction of fuel in a closed fuel cycle and the physical principles of fast breeder RU (accessed 20.03.2016). As a result, a strategy for generating nuclear power that does not require any structural improvements to existing reactors in the transition to thorium-containing fuel and enables the organisation of expanded fuel cycle reproduction is of great interest.

Today, Russian technology for implementing the thorium fuel cycle is innovative, but technically and economically underdeveloped due to the necessity of significant financial investments. However, given the potential benefits of a thorium cycle and the timeline of nuclear technology development and implementation, there is a demonstrated need for research concerning methods for employing thorium in both ongoing and new RU projects.

In previous studies (Shamanin et al., 2001; Shmelev et al., 2004; Haas et al., 1999; Petti et al., 2013), the authors examined the positive and negative features of thorium, allowing them to conduct an assessment of the effectiveness of thorium nuclear technology. They analysed nuclear fuel containing thorium in various types of RUs and demonstrated the feasibility of using thorium fuel in industrially produced reactors. These studies concluded that the introduction of a thorium fuel cycle with fast breeder reactors and commercial LWRs is relevant in present-day Russia. In these units, upgrades to existing thermal generator fuel assembly designs are possible and, under certain conditions, permit replacement of conventional uranium fuel with thorium fuel. However, in innovative reactor designs, many complex scientific and engineering problems remain before thorium fuel cycles can be implemented.

There have been a large number of projects that have investigated thorium as a possible fuel source. Intensive development toward this goal began in the mid-90 s, when the US Department of Energy recruited specialists from the National Research Centre Kurchatov Institute to work on the international Radkowsky Thorium Reactor project. In recent years, a number of innovative uses for thorium have been introduced (Petti et al., 2013; Kiryushin et al., 1997; Rowinski et al., 2015; Mascari et al., 2012; Black et al., 2015; Deniskin et al., 2007; Hidayatullah et al., 2015; Shamanin et al., 2015; Ponomarev-Stepnoy et al., 2010; Stainsby et al., 2011; Nabielek et al., 1990; Lee et al., 2009; Locatelli et al., 2014; Liem et al., 2016; Ismail et al., 2007; Hoai et al., 2016). For

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example, authors studied LWR using numerical experiments, simulating various nuclear fuel assemblies with different thorium oxide fuels, submerged in the LWR core (Shamanin et al., 2001; Shmelev et al., 2004; Haas et al., 1999). The experiment used realistic loading patterns and fuel assembly permutations. The results showed the viability of using thorium-containing fuel in industrially produced LWR. The LWR operated on an open fuel cycle and the core life and the fuel burn-up reached the record values. The core life was limited by the radiation hardening and brittleness of the construction materials. In other studies (Petti et al., 2013; Rowinski et al., 2015; Black et al., 2015), the authors examined 40 different designs for low- and medium-power reactors as well as innovative solutions that are currently in the design or licensing stages. Problems relating to thorium use in high-temperature, heavy water and light water reactors are currently being studied.

A promising direction in nuclear power development is the construction of low-power, high-temperature gas-cooled reactors (HTGR). In the last decade, the design and construction of low-capacity modular HTGRs have commenced. Today, HTGRs are under development in the United States, Russia, Germany, France and Japan, which have well-developed nuclear energy programmes. In studies (Petti et al., 2013; Rowinski et al., 2015; Black et al., 2015; Shamanin et al., 2015), the authors note that the development of HTGR is also accelerating in Korea, China, India and South Africa. Full-scale numerical experiments on multivariate RU models are available in (Petti et al., 2013; Kiryushin et al., 1997; Deniskin et al., 2007; Hidayatullah et al., 2015; Shamanin et al., 2015; Ponomarev-Stepnoy et al., 2010; Nabielek et al., 1990; Ismail et al., 2007; Hoai et al., 2016) and other studies that examined structural designs and methods employed in calculations. These studies provide detailed descriptions of the reactor core construction and neutronic calculation methods.

The advantages of HTGRs include their higher nuclear safety compared to conventional designs, high efficiency (40%–50%), the absence of phase transitions in the coolant, few problems in working surface corrosion, the use of a different fuel, overload during reactor operation and the simplified management of spent fuel. The main feature of HTGRs is the ability to generate high-temperature heat, which provides a range of applications for these reactors (Shamanin et al., 2015; Stainsby et al., 2011; Lee et al., 2009). The first HTGRs were developed for and implemented in operational models (1950–1960), but their commercial use in Russia as small modular reactors will not begin until 2020 at the earliest.

For Russia, a thorium fuel cycle based on domestic LWR- and BN-type sodium-cooled fast breeder reactor (e.g. BN-600, -800, -1200) is the most optimal method of nuclear energy development. Among the IV generation RUs, low-power Thorium High-temperature Gas-cooled Reactor Units (HGTRU) (up to 100 MWth) are significant, such that their implementation in Russia offers considerable potential to nuclear energy development. The existing BN-type reactors (which never entered industrial production due to high costs) combined with Russia's vast experience in creating low power enables HGTRU technology to be rapidly introduced. Furthermore, HGTRUs offer clear advantages in for supplying energy to the large naval bases and remote military garrisons in the Arctic and Eastern Siberia. In these regions, HGTRUs are ideal sources of energy, heat and hydrogen and do not require large bodies of water or rivers. Furthermore, HGTRUs are safe, cheap and can be quickly constructed (compared to industrially produced LWR or BN). HGTRUs power can also be altered in accordance with the growth of regional energy consumption.

On a global scale, low-power thorium reactors and related technologies are among the most expensive proposals per unit of generated power (Black et al., 2015; Locatelli et al., 2014). Such reactors should become the basis of regional energy in Russia other countries with high energy, heat and hydrogen demands. Thus, developing countries with relatively high levels of income, infrastructure and expanding business are suitable markets for HGTRU technology (Black et al., 2015; Locatelli et al., 2014). Reactors of this type can be supplied without nuclear proliferation infringements concerns. We note that industrial production of HGTRU will reduce the cost of construction and make the technology more competitive. The economic effects of HGTRU industrial production will be seen in the mass production of fuel, blocks and construction elements, as well as in the experience and knowledge acquired during use.

The main goal of this work is to study the neutronic characteristics of a low-power HGTRU with fuel blocks and pellets of different configurations. By conducting numerical experiments on the reactor physics using specialised software packages, the inconsistencies between nuclear physics constants (cross sections) of evaluated nuclear data files should be taken into consideration.

Few previous studies (Ridikas et al., 2002; Liem et al., 2016; Talamo et al., 2004; Vu et al., 2013; Plevaka et al., 2015; Mai et al., 2012; Unesaki et al., 2004) show inconsistencies between ENDF/B (USA), JEFF (Europe), JENDL (Japan), ROSFOND (RF) and other evaluated nuclear data files. Studies dealing with various reactor designs with thermal and fast-neutron spectrums using a uranium (Liem et al., 2016) and plutonium fuel cycle (Ridikas et al., 2002; Talamo et al., 2004) demonstrated that the value of the effective neutron multiplication factor (k_{eff}) and several other neutronic parameters are independent of the database selection.

Previous studies (Liem et al., 2016; Vu et al., 2013; Plevaka et al., 2015; Mai et al., 2012; Unesaki et al., 2004) analysed the nuclear physics constants of evaluated and other nuclear data libraries. Innovative RU designs (e.g. high-temperature gas-cooled reactor, gas turbine modular helium-cooled reactor, breed-and-burn reactor) that operate on uranium and thorium fuel cycles (Liem et al., 2016) are also studied. The need to adjust the nuclear data used in the calculation of $k_{inf}(t)$ (Liem et al., 2016; Vu et al., 2013; Plevaka et al., 2015; Mai et al., 2012; Unesaki et al., 2004) is demonstrated in the literature. Thus, while calculating the reactor core with thorium fuel, we must take into account inconsistencies between nuclear physics constants of evaluated nuclear data files.

To avoid obtaining erroneous results, we used verified WIMS-D5B (Daniel and Aldama, 2000) and MCU-5 (Kalugin et al., 2015) calculation codes. The WIMS-D5B (Daniel and Aldama, 2000) code is to calculate reactors of various types. WIMS-D5B uses a 69-group system of constants based on the ENDF/B evaluated nuclear data files. The ENDF/B (ENDF/B-V and later versions) data with satisfactory precision (~30%–40%) is consistent with both the experimental and JENDL, JEFF, ROSFOND evaluated nuclear data. Most researchers recommend using ENDF/B (Liem et al., 2016; Vu et al., 2013; Mai et al., 2012; Unesaki et al., 2004) to calculate $k_{inf}(t)$ for thorium reactors.

The MCU-5 (Kalugin et al., 2015) code was developed by National Research Centre Kurchatov Institute and is intended for modelling particle (e.g. neutrons, photons, electrons and positrons) transitions in any reactor using the Monte Carlo method. MCU-5 uses its own data bank, MCUDB50, while MCUDB includes the ACE/MCU and BNAB/MCU nuclear files. ACE/MCU is a point-wise representation of neutronic constants based on evaluated nuclear data files (ENDF/B, JEFF, JENDL, ROSFOND) and BNAB/MCU is an expanded and modified version of the BNAB-93 26-group system of constants. We note that ROSFOND includes cross-section data of neutron interactions with thorium isotopes from JENDL-3.3, ENDF/B-VIIb2, JEFF-3.1 and EAF-2003, as well as experimental data from the Evaluated Nuclear Structure Data File (ENDFSF) and Experimental Nuclear Reaction Data (EXFOR). The main source of ROSFOND is the ENDF/B, and JENDL evaluated nuclear data files.