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The utilization of thorium in Generation IV reactors

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ABSTRACT

The main goal of this paper is to show how thorium, as an alternative nuclear fuel, could be applied as fuel in a Generation IV reactor. The paper focuses on the multiplication factor, the produced ^{233}U and delayed neutron fraction in infinite lattice models. For the investigations, simplified models of a fuel assembly of five design types of the six reactor concepts were elaborated. The MSR reactor type is out of scope of this paper due to the fact that it is designed for the utilization of thorium. Although the fissile isotope content was not increased to compensate the thorium caused multiplication factor decrease, the burnup calculations suggest that the designs of ESFR (European Sodium-Cooled Fast Reactor) and ELSY (European Lead-cooled System) are the most promising types according to the trend of the multiplication factor changes and the amount of produced fissionable ^{233}U.

1. Introduction

Thorium can be the prospective fuel for nuclear reactors. The great availability makes this material a potential replacement of uranium. However, it does not contain any fissionable isotope so it is impossible to start a fission chain reaction based solely on thorium. Nevertheless, thorium can be converted to fissionable ^{233}U. In the past, several facilities were constructed to research thorium, e.g. Elk River BWR, Peach Bottom HTR, Edison Indian Point-1 PWR, Shippingport PWR, etc. Nowadays theoretical as well as experimental research programs, such as the irradiation program in the Halden reactor aim to determine how thorium could be optimally utilized in nuclear reactors (OECD, 2015).

A few features of thorium which could induce the renewed interest:

- Higher burnup levels can be achieved with thoria-based fuels.
- Thorium fuels can be more accident tolerant because of its higher melting temperature and improved thermal characteristics.
- Lower production of plutonium and MAs in thorium/uranium fuels in general.
- High conversion factors can be reached.
- In LWR fuels, adding thorium can improve the ceramic properties (OECD, 2015).

Since Generation IV reactors are designed to be used in the period around 2030 and beyond (GIF, 2014), it can be interesting to know how thorium fuel can influence the fuel cycle of these reactors.

2. Generation IV reactors

Nuclear energy offers a very effective low carbon source of energy. This is the reason why many countries are building or planning to build nuclear reactors nowadays. Mainly Generation II reactors are operating these days but the technology of Generation III reactors is available as well. Although these are evolutionary designs, the innovative designs of the Generation IV reactors obtain significant attention because of the improved safety, sustainability, economics and proliferation resistance. The members of the Generation IV International Forum selected six reactor-types which can be promising. These are the Very-High-Temperature Reactor (VHTR), the SuperCritical-Water-cooled Reactor (SCWR), the Sodium-cooled Fast Reactor (SFR), the Gas-cooled Fast Reactor

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(GFR), the Molten Salt Reactor (MSR) and the Lead-cooled Fast Reactor (LFR) (GIF, 2014). These reactors have many concepts, which can have completely different construction and may contain different fuel assemblies. In this paper, five of the six reactor concepts are investigated (MSR (Serp et al., 2014) is excepted).

3. Thorium

Natural thorium consists of essentially one isotope, ^{232}Th. Thorium is a fertile material which, upon capturing a neutron, may undergo a series of nuclear decay processes, leading to the fissile ^{233}U. The neutron capture, which leads to this isotope, is interrupted by two intermediate nuclei, ie. ^{233}Th and ^{233}Pa. It is important to highlight that ^{233}Pa has a significant neutron capture cross section and leads to ^{234}U which is not fissionable. From another perspective, ^{233}Pa is similar to ^{239}Np in the case of U-Pu cycle; however, ^{239}Np has a much shorter half-life (about 2.35 days vs. 27 days for ^{233}Pa) and smaller neutron cross sections. Because of these properties, ^{233}Pa can be a significant neutron poison in the case of Th-U, or for the mixed Th-U and U-Pu cycles (Belle and Berman, 1984).

Thorium based fuel materials have higher melting point than the uranium based ones, which is advantageous for safety. It is important to mention that the recycling of thorium-based fuels is more difficult due to the ^{232}U contaminant. This isotope produces strong gamma and alpha radiation, and its half-life is 1.9 years. The entire spent fuel handling process must be done under proper remote conditions. However, this can help proliferation resistance as well. A further disadvantage is the fact that much less information is known about thorium and its behaviour than about uranium or plutonium (Belle and Berman, 1984).

4. The performed investigations

A single concept of each reactor type, which contains solid fuel, was modelled. For the calculations, MCNP6 was used (Goorley et al., 2016; Fensin et al., 2015; Fensin and Umbel, 2015). Each calculation was performed for a single fuel assembly with reflective boundary conditions (infinite lattice model). However, in axial direction the designed physical sizes of the fuel assemblies with reflectors were taken into account. This enables neutron leakage in axial direction; in radial direction it is neglected. In each case fresh fuel was used initially and the amount of thorium-containing fuel pins was varied in the models. Thorium was applied in a similar way as uranium in each case: ThO_2 was used if uranium is in UO_2 matrix, and ThC if uranium is in uranium-carbide matrix. The calculations simulated 500 effective days (EFPD). The first timestep was after 2 EFPD and then on every 50th day. The number of active cycles was 1000 per time step and the number of starting neutrons was 2500 per cycle in each burnup calculation. For the delayed neutron fraction calculations, the number of active cycles was 2000 with 10,000 neutrons per cycle for better statistics. Since the applied thorium changes the neutron spectrum, this was also investigated for BOC and EOC as well. Hence the increasing amount of thorium decreases the fissionable isotope content in the investigated cases, it also decreases the initial multiplication factor. This was not compensated in the calculations. In this way, the paper focuses mainly on the trend of the infinite multiplication factor and the delayed neutron fraction changes. The models are similar to those presented in (György and Czifrus, 2015). The main difference is that the applied ENDF-VII cross section library contains more accurate temperatures than that used in (György and Czifrus, 2015).

For the calculations described below the authors did not change the main design parameters, such as lattice geometry, assembly height, coolant properties. The application of thorium in the fuel assemblies of the investigated reactor types may move them away from the designed operating parameter set. Nevertheless, as many currently operating reactors operate outside of the original design envelope (Heraltova; Gehin et al., 2004; Gagarinskiy and Saprykin, 1035), the results of this study may be broadly applicable.

Table 1
The thorium volume ratio of the fertile particles in the investigated cases.

Case	Thorium ratio compared to the fertile particles	Thorium ratio compared to the fissile particles
Reference case	0.00%	0.00%
First case	15.38%	18.81%
Second case	30.77%	37.62%
Third case	46.15%	56.43%
Fourth case	100.00%	122.26%

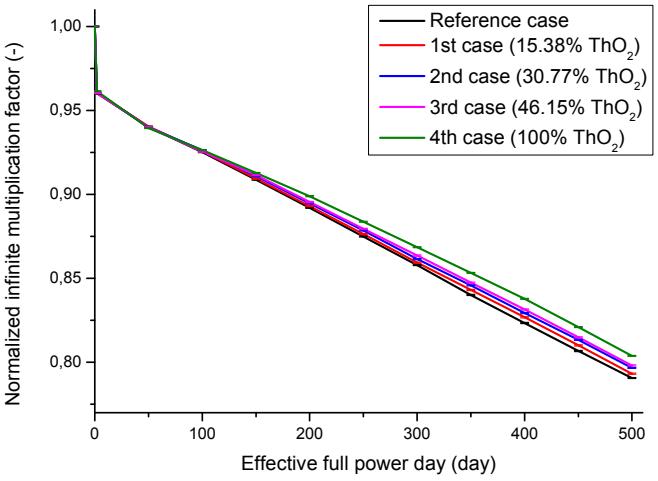

Fig. 1. The change of the normalized infinite multiplication factors in the VHTR reactor.

4.1. VHTR

The Very High Temperature Reactor is a helium cooled graphite moderated thermal reactor. In this paper, the concept with TRISO fuel particles was modelled, the design of which resembles the GT-

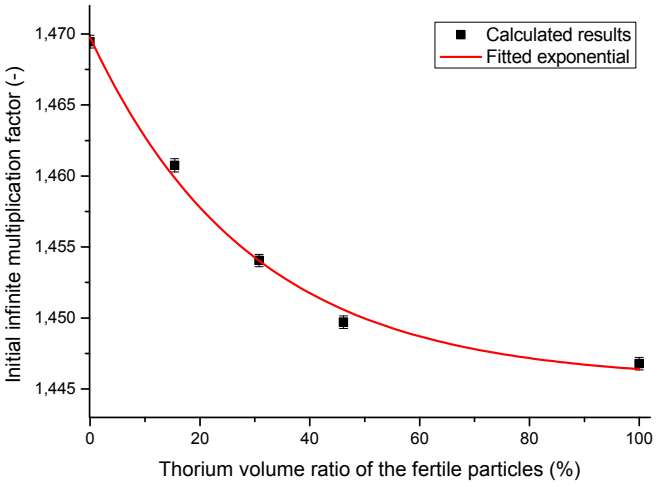

Fig. 2. The change of the initial multiplication factors in the VHTR reactor.