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The utilization of thorium in Small Modular Reactors – Part I: Neutronic assessment

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ABSTRACT

This work presents a neutronic assessment to convert a Small Modular Reactor (SMR) with uranium core to the thorium mixed oxide core with minimum possible changes in the geometry and main parameters of SMR core. This option is due to most of SMR are designed to be strongly poisoned in the beginning of cycle and to have a long cycle. Thorium can be used as an absorber in the beginning of the cycle and also be used as a fertile material during the cycle, it seems to be a good option to use $(Th/U)O_2$ as SMR's fuel. The main neutronic objectives of this study is achieving longer cycle length for SMR by using the minimum possible amount of burnable poison and soluble boron in comparison with reference core. The Korean SMART reactor as a certified design SMR has been chosen as the reference core. The calculations have been performed by MCNP code for homogeneous and heterogeneous seed and blanket concept fuel assemblies. The results obtained show that the heterogeneous fuel assembly is the one which gives longer cycle length and used lower amount of burnable poison and soluble boron, and also consumes almost the same amount of ^{235}U.

1. Introduction

During the past decades, most of nuclear power has been produced by water cooled reactors that use UO_2 as fuel in a once through fuel cycle. The high rate of uranium consumes, make the natural resource of this fuel limited to this century even at the high cost of uranium ore (NEA/IAEA, 2016). To increase the utilization of uranium, the plutonium has been already recycled in thermal reactors and it is use as mixed oxide fuel (MOX) of U/Pu in the same reactors (OECD/NEA, 2007). Another option is the utilization of (thorium/uranium) oxide as a mixed fuel.

The natural thorium isotope (^{232}Th) as a fertile fuel can finally be converted to a fissile ^{233}U isotopes after a thermal neutron capture reaction. It has been estimated that thorium is approximately three times more abundant than uranium present in the earth's crust (IAEA, 2000).

Using of Thorium base fuel option in nuclear reactor has many advantages: the highest number of neutrons produced per neutron absorbed among all thermally fissile isotopes; neutron poison (Xenon and Samarium) production is 20% lower than other fissionable isotopes; reducing the radiotoxicity of the spent fuel, and non-proliferation. Besides the neutronic advantages, Thorium oxide (ThO_2) is relatively inert and does not oxidize further, unlike UO_2. It has higher thermal conductivity and lower thermal expansion coefficients compared to UO_2, as well as a much higher melting point (3300 °C). The fission gas release in irradiated nuclear fuels is much lower than in UO_2. These properties tend to improve the nuclear and thermal hydraulic characteristics of Uranium and Thorium mixed oxide fuels compared to current uranium oxide fuels (Kutty et al., 2013).

The thorium fuel has been used in Shippingport reactor core and successfully showed breeding of ^{233}U. The Radkowsky seed and blanket concept (seed is an U/Zr alloy and the blanket is $(Th_{0.9}$-$U_{0.1})O_2$) has been used in the last core of the Shippingport reactor with high enriched uranium fuel (HEU) and 1200 effective full power days and final burnup of 60 MWD/kg (Kasten, 1998).

Recently, the feasibility of using Thorium in different kind of reactor has been studied: Tucker et al. (2015, 2018) have studied

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the using of a thorium–plutonium mixed oxide fuel for a Westinghouse-type 17 × 17 PWR; Maiorino et al. (2017a, 2017b, 2014) have investigated the using of (U-Th)O_2 fuel for PWR reactors; Permana et al. (2011) have analyzed the heavy metal closed-cycle water cooled thorium reactor; Lindley et al. (2014) have studied the closed thorium-transuranic fuel cycle in reduced-moderation PWRs and BWRs and Ashely et al. (2014) have modelled the open cycle thorium-fuelled nuclear energy systems. In this work, the possibility of using Thorium fuel for the new type of reactors, that known as Small Modular Reactors (SMRs), will be evaluated.

SMRs aren't a new concept but they are an idea whose time has come. Over the past decade, SMRs have increasingly been recognized as a potential alternative to large-scale nuclear reactors. The International Atomic Energy Agency (IAEA) classifies any nuclear reactor with a power output of less than 300 MWe as small. Those with outputs between 300 and 700 MWe are considered medium-sized reactors, while those with outputs greater than 700 MWe are classified as large reactors (IAEA, 2016).

SMRs ("modular" because many of major components can be assembled anywhere far from the sites and then shipped to the main sites) have been getting a lot of positive attention in the recent years, although the nuclear energy industry has tried to be economically viable. SMRs may present many advantages over older technologies including: the possibility to construct in a modular way, reducing up-front capital costs by simpler, less complex power plants. SMRs designs can also bring more efficiency and inherently safe systems. Furthermore, besides electricity generation, SMRs could be used in all energy systems like district heating, co-generation, energy storage, desalination, or hydrogen production.

According to the IAEA report currently, at least 50 SMR designs for different application are under various stages of design, licensing and construction all over the world. Three of these SMRs are under different stages of construction: KLT40s (a floating power unit from Russia), HTR-PM (a high temperature gas cooled reactor from China) and CAREM (an integral PWR from Argentina). These three SMRs are planned to start their operation between 2017 and 2020. Furthermore, the Korean Nuclear Safety and Security Commission approved the Standard Design of the 100 MWe System Integrated Modular Advanced Reactor (SMART). Also, there are many other of SMR designs that will be prepared for near term deployment. According to the IAEA report realistically it seems that the first commercial group of SMRs, start operation near 2025 – 2030. Although, large group deployment of SMRs will only occurred beyond 2030 (IAEA, 2016).

Due to this great interest in developing SMRs, researchers all over the world are trying to survey different aspect of these reactors (Akbari-Jeyhouni et al., 2018; Nian, 2017). Iyer et al. (2014) surveyed the SMRs as a solution for climate changes or Cooper (2014) tried to evaluate the role of the SMRs in the future of nuclear power. Also, there are several researches about safety and thermal hydraulic features of SMRs (Zaman et al., 2017; Li et al., 2017). In this work, we try to introduce an alternative fuel for SMRs fuel. SMR cores are designed to stand for a complete cycle, without the need to be refueled, but they need to be strongly poisoned at the beginning of life. So, since thorium can be used as a poison and also a fertile fuel, it could be a good option to be used as mixed oxide with uranium, and so we could reduce the burnable and soluble poison and also have an extended burnup cycle.

In this study, we used Korean SMART reactor (the SMR reactor that has received design certification (IAEA, 2016)) as the basis of our calculations. An assessment has been performed to achieve 5-year cycle SMART core design using thorium fuel by using more enrichment of uranium (20 wt%) mixed with Thorium and increasing the burnable poison amounts for SMART core design in its conceptual design status (Cho et al., 2000; KAERI/TR-1775, 2001), while in present work, it has been tried to keep the fuel enrichment below 5 wt% and using lower amounts of burnable poison and soluble boron for the final design of SMART core after its licensing stage. The main purpose of this study is to obtain a new core configuration in which we convert the reference SMART core to one with (U/Th)O_2, with the same geometry and operational parameters for the all core components, as much as possible. The objective of the work is to demonstrate the design feature of the proposed (U/Th)O_2 core.

The remainder of the paper is organized as follows. Section 2 presents an overview of the SMART reactor and its operational parameters. In Section 3, the material and methods including calculation procedure, MCNP code, (U/Th)O_2 SMART core configurations and verification of calculations have been presented. Section 4 presents the results of the calculations for different mixed U/Th SMART core configurations that have been compared with reference SMART core and finally, conclusion and remarks are given in Section 5.

2. Description of SMR case

Korean Atomic Energy Research Institute (KAERI) has been developing the system-integrated modular advanced reactor, an advanced integral pressurized water reactor, since 1997. The conceptual and basic designs of SMART with a desalination system were completed in March of 1999 and March of 2002. SMART Pilot Plant and Pre-Project for the SMART were completed in 2006 and 2007, respectively. In July 2012, the Korean Nuclear Safety and Security Commission issued the Standard Design Approval for the SMART (IAEA, 2016).

SMART is expected to be one of the first new Nuclear power plants in the range of 100 MWe, which is a very useful energy for various industrial applications. This SMR has been designed with enough output to meet the fresh water and electricity

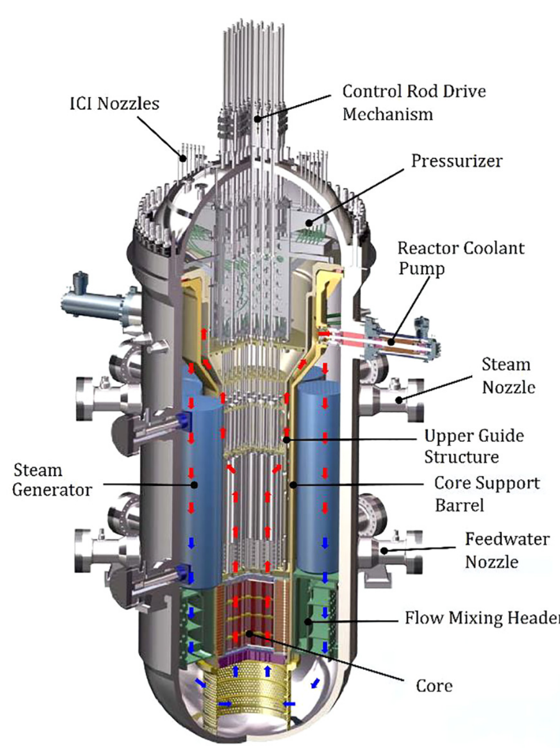

Fig. 1. Schematic view of Korean SMART reactor (IAEA, 2011; Lee, 2010).