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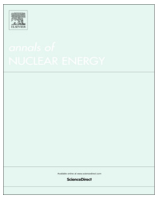

Comparative neutronic study of homogeneous and heterogeneous thorium fuel based core design in a lead-cooled fast reactor

Luis-Carlos Juárez-Martínez, Juan-Luis François *

Universidad Nacional Autónoma de México, Facultad de Ingeniería, Departamento de Sistemas Energéticos, Paseo Cuauhnáhuac 8532, Col. Progreso, 62550 Jiutepec, Morelos, Mexico

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ABSTRACT

In the present work the utilization of thorium is investigated in a lead-cooled fast reactor. Two thorium fuel strategies were analyzed: a homogeneous and a heterogeneous mixture of ^{232}Th were set in the European Lead-cooled Fast Reactor core model. For this, the Monte Carlo Serpent-2.27 code and the JEFF-3.1 cross section library were used to perform the calculations. Three neutronic parameters were analyzed for each fuel strategy: the effective neutron multiplication factor (*keff*) for a cycle of 900 days, the Doppler constant and the reactivity effect of coolant density. With the homogeneous mixture of ^{232}Th the neutron multiplication factor increases during the whole operating cycle (900 days), allowing a longer fuel cycle, keeping negative values for the Doppler constant and the reactivity effect of coolant density, with -692 pcm and -148 pcm, respectively. On the other hand, the addition of ^{232}Th heterogeneously in the core showed that there is the necessity to have a reactivity excess around 2.2% Δk to fulfill the same fuel operating cycle. Even when there is a ThO_2 blanket zone, the ^{233}U production is not enough to increase the *keff* value and to enlarge the fuel operating cycle. Otherwise, the Doppler constant and the reactivity effect of coolant density are also negative values.

1. Introduction

In order to reduce greenhouse gas emissions and fulfill the future global energy demand, nuclear power, as a low carbon technology, becomes an important energy source able to satisfy the global energy demand and reducing the environmental impact (IAEA, 2016).

Taking into account the need of a global decarbonisation mainly by electricity generation, in 2002 six reactor technologies were selected. This generation IV (GENIV) promises to be more safe, economic, sustainable, and more proliferation resistant than the previous generations. Currently, several countries around the world work together on the development of the so-called GENIV reactors, and it is expected that they will reach a commercial level by the year 2030 (GENIV, 2017).

Most of the aforementioned reactors use UO_2 and MOX as fuel. Regarding the sustainability goal, it is necessary to have fuel alternatives that allow a better use of the resources in order to extend the nuclear energy life. Therefore, thorium being three to four times more abundant than uranium over the Earth's crust becomes an excellent candidate to be used as nuclear fuel. However, due to the lack of fissile content in natural thorium it is necessary to convert the fertile isotope ^{232}Th into the fissile isotope ^{233}U, and a good option to carry out this process are the fast reactors, since the high neutron flux that facilitates the transmutation process (György et al., 2016).

For this work, the European Lead-cooled Fast Reactor (ELFR) model has been selected (Stanisz et al., 2016). The ELFR has a MOX based fuel, therefore it is pretended to analyze the reactor behavior with the inclusion of thorium to take advantage of its breeding capability.

Then, the main goal of this paper is to analyze the core behavior using the fertile material ^{232}Th in the ELFR fuel. For this, two fuel strategies were analyzed, based on a reference fuel vector, composed with a mixture of (U/Pu/MAs), which was modified as follows: at first, all the uranium isotopes were replaced for a mixture of ^{232}Th/^{233}U keeping constant the Pu and Minor Actinides (MAs) vectors, this fuel composition was called (Th-Homogeneous) fuel. At second, three different fuel compositions were set in the core: one with the reference fuel vector, second with a mixture of (^{232}Th/^{233}U/ Pu/MAs), and a third with ThO_2 as blanket. Due to the use of different fuel compositions, in this case the fuel was called (Th-Heterogeneous). The Monte Carlo Serpent-2.27 code (Leppänen et al., 2015) with the JEFF-3.1 cross section library were used to perform the calculations.

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* Corresponding author.
E-mail addresses: lcjm@ier.unam.mx (L.-C. Juárez-Martínez), jlfl@fi-b.unam.mx (J.-L. François).

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The structure of this paper is as follows: The ELFR concept along with its main characteristics is described in Section 2. Section 3 presents the ELFR core. In Section 4 the Th-Homogeneous fuel analysis is presented, and in Section 5 the Th-Heterogeneous fuel analysis is showed. Sections 6 and 7 depict the nuclide inventories and the neutron energy spectrum obtained for each analyzed case. In Section 8 the axial and the radial power distributions obtained for both fuels are presented and discussed, and finally the conclusions are provided in Section 9.

2. The European Lead-cooled Fast Reactor (ELFR)

The ELFR is an evolutionary design of its predecessor ELSY (European Lead-cooled System). It is a 1500 MWt fast critical reactor with pool-type configuration. This configuration allows containing all the primary coolant within the vessel, avoiding problems related to the primary coolant circulation out of the vessel. The fuel selected is an equilibrium mixture of U/Pu/MAs (Grasso et al., 2013). The main aim of the ELFR is to demonstrate the viability of a safe and sustainable reactor concept through the exploitation of intrinsic properties of lead, in addition to achieving economic competitiveness (Grasso et al., 2013).

The ELFR is designed to keep constant the transuranic elements (TRUs) inventory, from cycle to cycle. This goal is achieved by a closed fuel cycle, where all the transuranic elements are transmuted within the reactor, so there is no exchange of TRUs between the reactor and the environment except for losses due to fuel reprocessing; this concept is known as adiabatic reactor. In other words, the reactor consumes only natural or depleted uranium and produces only fission products (Artioli et al., 2010). To say that the reactor operates under an adiabatic condition, the fuel composition and criticality must be the same from cycle to cycle, in addition the core breeding (CB) must be zero for the whole cycle (Stanisz et al., 2016).

3. Description of the ELFR core

A neutronic modelling of the ELFR in adiabatic equilibrium state has been developed by Grasso et al. (2013); study from which the dimensions, characteristics and materials of the reactor were taken. Table 1 shows the main characteristics of this fast reactor and Fig. 1 depicts a radial view of the core which is divided in 8 radial zones each one represented with different color. Even when the fuel composition is the same for each radial zone, this nodalization is very helpful for fuel management purposes and was kept from the reference study (Grasso et al., 2013). The reactor core consists of 427 hexagonal fuel assemblies (FA) with an active height of 140 cm. The FA are surrounded by 132 shield assemblies made of Y-stabilized zirconia. The FA are conformed by 169 fuel pins coated with the Stainless Steel T91; this material was also used as structural material, e.g. channel walls, core barrel, upper and lower plugs.

The fuel is divided in two sets of fuel assemblies; the first set of 157 FA and the second set of 270 FA. The difference among these sets is the volumetric fraction of fuel, the first set of FA has a central pellet hole of 4 mm and the second set has a central pellet hole of 2 mm. These holes were designed to keep the radial power distribution flatten, without changing the fuel enrichment (in terms of Pu), then the shape of the power is reached only by varying the volumetric fraction of fuel. The first set of FA is called Inner Fuel (IF), and the second set of FA is called Outer Fuel (OF).

The core has 12 Control Rods (CR) and 12 Safety Rods (12), which are not modeled in this work. In addition, two lead densities were set for the neutronic modeling, one of 10.58 g/cm^3 in the inlet region and 10.478 g/cm^3 in the in-core and outlet region; besides, a natural lead composition was used taking into account the intrinsic impurities of lead in order to have a more realistic model. Finally, the reactor core is submerged in a pool full of lead with a total height of 610 cm, and 680 cm of diameter. The core barrel has a diameter of 560 cm with 5 cm of thickness, see Fig. 2.

Table 1
Main ELFR parameters.

Parameter	
Power [MWth/MWe]	1500/600
FA geometry	Hexagonal
Fuel	MOX + MA
Fuel temperature [K]	1200
Cladding temperature [K]	600
Coolant	Lead
Coolant temperature [K]	600
Number of fuel assemblies	427
Number of fuel pins	169
FA pitch [mm]	209
Pin pitch [mm]	15
Wall channel thickness [mm]	5
Clearance between FAs [mm]	5
Active height [mm]	1400
Hole pellet inner/outer [mm]	4.0/2.0
Pellet outer diameter [mm]	9
Pellet inner diameter [mm]	4
Fuel pin clad thickness [mm]	0.6
Fuel pin gap thickness [mm]	0.15
Number of CR	12
Number of SR	12
Number of shield assemblies	132
Barrel diameter [mm]	5600
Barrel thickness [mm]	50

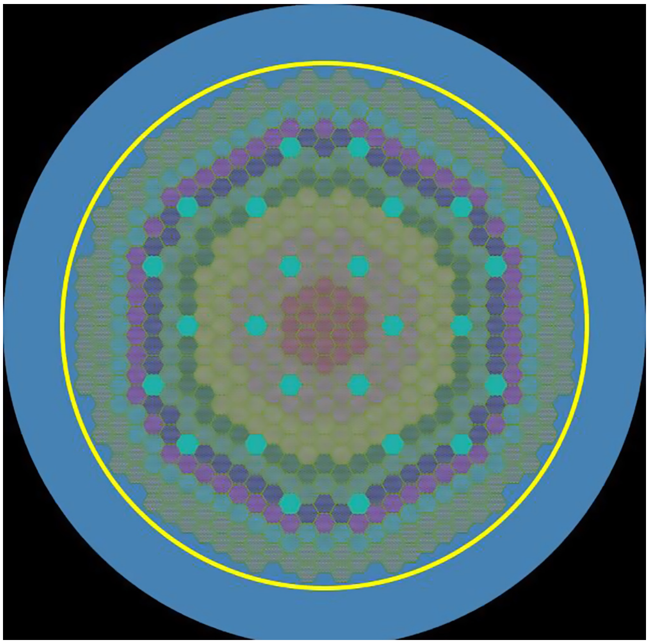

Fig. 1. Lead-cooled Fast Reactor core (Serpent model).

It is important to mention that a previous validation work of our Serpent model used in this study, was performed for this ELFR core and presented in the 2017 ANS Winter Meeting & Nuclear Technology Expo, 2017 (Juárez-Martínez and François, 2017).

In Table 2 the reference fuel vector is presented.

4. Thorium-Homogeneous fuel analysis

As it was mentioned before, in this analysis all the uranium isotopes of the reference fuel vector were replaced for a mixture of