Annals of Nuclear Energy xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Investigation of different scenarios of thorium–uranium fuel distribution in the VVER-1200 first core

Mohammed S. Dwiddar [a,*], Alya A. Badawi [a], Hanaa H. Abou-Gabal [a], Ibrahim A. El-Osery [b]

[a] Department of Nuclear and Radiation Engineering, Faculty of Engineering, Alexandria University, Lotfy El-Sied st. off Gamal Abd El-Naser, Alexandria 11432, Egypt
[b] Nuclear Power Plants Authority, 4 El-Nasr Avenue, P.O. Box 8191, Nasr City, Cairo 11371, Egypt

ARTICLE INFO

Article history:
Received 6 December 2014
Received in revised form 8 June 2015
Accepted 10 June 2015
Available online xxxx

Keywords:
Mixed thorium–uranium fuel
Seed-blanket fuel
VVER-1200

ABSTRACT

Thorium fuel gives some superiority from safeguards point of view and is now being considered as an option for nuclear fuel. It is found to achieve high proliferation resistance because it has significant lower production of plutonium and minor actinides as compared with uranium fuel. The effect of the insertion of thorium, as a part of the nuclear fuel, on the neutronic parameters of the VVER-1200 first core under normal operation was studied. Two different patterns, namely mixed thorium uranium fuel and seed-blanket fuel, were compared. In addition to the amount of the inserted thorium, it was found that the position of the thorium assemblies inside the reactor core plays an important role in determining the effective multiplication factor and hence the core cycle length. It was concluded that the best location of thorium is in the periphery of the reactor core. As the preparation of thorium fuel does not involve all the requirements imposed by the uranium fuel, it is therefore expected that the economical feedback of both uranium–thorium fuels will be also positive, especially for a country with high thorium abundance.

1. Introduction

Generation III+ nuclear reactors have several advantages, for example, the ability to achieve high fuel burn-up, thus leading to efficient use of the fuel and reduced waste amount. In addition, they have the ability to accommodate different kinds of fuels. Recently new fuel compositions as Thorium–Uranium (ThO_2–UO_2) and Thorium–Plutonium (ThO_2–PuO_2) fuels have been considered and showed promising results to enhance and increase the effectiveness of the nuclear fuel.

Thorium is 3–4 times more abundant than uranium and is widely distributed in nature as an easily exploitable resource in many countries. Unlike natural uranium, which contains ~0.7% fissile ^{235}U isotope, natural thorium does not contain any fissile material and is made up of the fertile ^{232}Th isotope only. Hence, thorium and thorium-based fuel as metal, oxide or carbide, has been utilized in combination with fissile ^{235}U or ^{239}Pu in nuclear research and power reactors for conversion to fissile ^{233}U, thereby enlarging the fissile material resources (IAEA, 2005).

Past experience and current technology suggest the possibility of improving of economics and safety by introducing thorium in the nuclear fuel. This possibility was studied from the core design and fuel management point of view considering the Western Westinghouse PWR whose fuel assembly is characterized by 17 × 17 rod array. Enriched uranium not exceeding 20 w/o ^{235}U as fissile material was used (Zhao, 2001). However, this assumption does not conform to the international practice rules stating that the enrichment of the light water reactors fuel cannot exceed 5%. It was concluded that mixed ThO_2–UO_2 fuel will not provide an economically superior performance to the all-UO_2 fuel. The heterogeneous seed and blanket fuel design concepts improve the thorium fuel utilization, since the thorium fuel may stay in the core for a longer time that the uranium (Wang, 2003).

In this paper, thorium oxide was investigated as a fuel component replacing a part of the UO_2 fuel within the Russian VVER-1200 reactor core model for long term development strategy. The two different patterns, namely mixed thorium uranium fuel and seed-blanket fuel, were tested in the reactor case study from a neutronic point of view. Different thorium uranium reactor core configurations were considered with the main objective to maximize the first core cycle length. But since an important target of using thorium fuel is to breed the fissile isotope ^{233}U, the evolution of the actinides inside the core was also examined.

2. Reactor core modeling

Fig. 1 illustrates the two configurations of the ThO_2–UO_2 fuel lattices applied in this work. In the mixed thorium uranium fuel

* Corresponding author.

http://dx.doi.org/10.1016/j.anucene.2015.06.015
0306-4549/© 2015 Elsevier Ltd. All rights reserved.

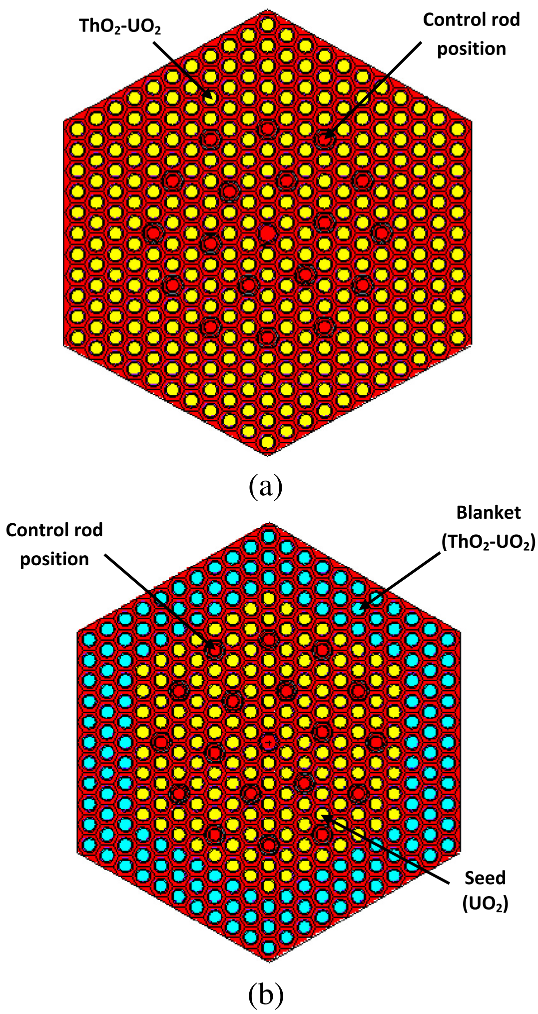

Fig. 1. ThO_2–UO_2 fuel lattice, (a) mixed thorium uranium fuel, (b) seed-blanket fuel.

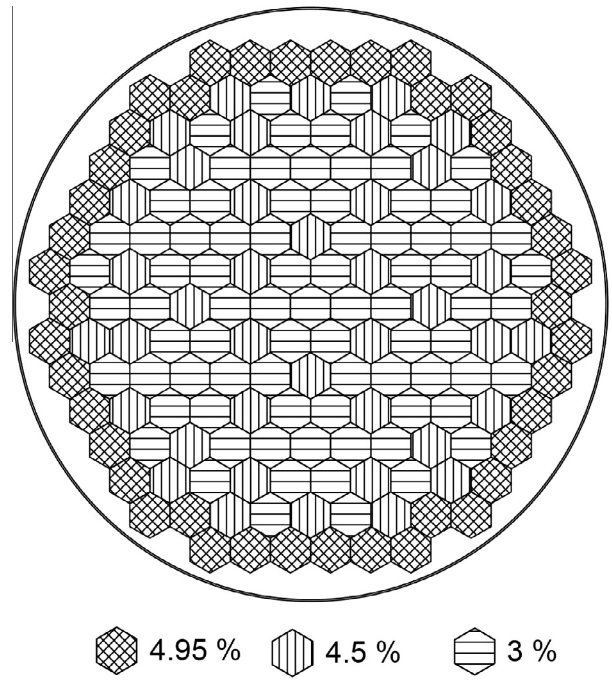

Fig. 2. Uranium fuel enrichment configuration in VVER-1200 first core.

Table 1
Reference case initial fuel composition.

Nuclide	Atom density (1/cm^3)	Weight percent (w/o)
U-235	8.906E+20	3.408
U-238	2.187E+22	84.74
O-16	4.551E+22	11.85

case (Fig. 1a), the standard UO_2 fuel rods are replaced one-for-one by ThO_2–UO_2 rods in a homogeneous state for all assembly's rods. The 100% UO_2 fuel rod is modified to be composed of a mixture of 50% UO_2 and 50% ThO_2. As to the seed-blanket fuel case (Fig. 1b), the seed part contains uranium dioxide fuel while the blanket part contains both uranium dioxide and thorium dioxide fuel.

The core configuration developed within the context of Dwiddar et al.'s previous work on the VVER-1000 reactor core and its improvements to achieve the new design of VVER-1200 reactor core (Dwiddar et al., 2014) was adopted in this work as the reference case. It was made up of uranium fuel with its maximum allowable enrichment under the international practice for the PWRs as shown in Fig. 2. The initial composition of the reference core fuel is listed in Table 1. The core is surrounded radially by a stainless steel reflector (buffer) similar to the one used in the VVER-1000 (IAEA, 1995). Axially, the top of the core was considered covered by a layer of water with height equal to 0.5 m. In addition, a layer of 0.5 m water was also considered under the bottom of the core.

Six different configurations regarding the distribution of the mixed thorium uranium fuels, in addition to three different configurations of the distribution of the seed-blanket thorium uranium fuels, were examined. The different cases under consideration are listed in Tables 2 and 3; the initial fuel compositions in each case are tabulated as well.

Monte Carlo N-particle X version (MCNPX) computer code system (Los Alamos National Laboratory, 2008) was used to perform the neutronic analysis of the reactor core in all the cases. Each case involved the tracking of 100,000 particles using 500 cycles per time step. The code was used to calculate the effective multiplication factor (k_{eff}) as well as the fuel burnup. The new depletion capabilities of the code facilitate tracking of the changes in each fuel assembly's composition for any reactor core under consideration. For the burnup calculation, the adopted model considered the fissile material in each assembly distributed in a heterogeneous way inside the fuel rods. The total volume of the fissile material in each assembly was then calculated. Accordingly, the total power generated in each assembly was computed.

3. Results

3.1. k_{eff} values

Based on the reactor's nominal thermal power (3200 MW), the k_{eff} value of the reference case was found to decrease as shown in Fig. 3, indicating that the reactor has to be refueled after 630 days. Fig. 3 illustrates the changing of k_{eff} with time for the six mixed thorium uranium reactor core cases as well. It can be noticed that cases 1, 2, 3 and 5 have a value of k_{eff} higher than 1 in the beginning of cycle (BOC). Cases 4 and 6 were excluded for their low k_{eff} values as they are less than one from the BOC.

Case 3 had the highest k_{eff} value following the reference case (Fig. 3). This can be explained by the fact that the replacement of half of the UO_2 with the ThO_2 occurred only in the periphery assemblies where the neutron flux is relatively low. Case 1 showed