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Homogeneous Design and Neutron Analysis for a Sodium-Cooled Fast Modular Nuclear Reactor

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Abstract. In this work, a neutron analysis for a homogeneous nuclear reactor core model with SMR characteristics and fast neutron spectrum has been analyzed. A mixture of uranium and thorium has been used as fuel, with the intention of incorporating thorium and verifying its behavior as a new nuclear fuel in this type of reactor. Sodium has been used as a refrigerant element. Several scenarios with different levels of enrichment for U-235 were evaluated. Monte Carlo simulations were carried out for an irradiation period of 650 days, emphasizing the analysis of the effective multiplication factor, the inventory of fission products and minor actinides of interest, and the degree of fuel burnup. It was obtained that for an enrichment of 17% the reactor could operate at nominal power in a supercritical state, in addition to low production of Pu-239.

Keywords: Uranium, thorium, criticality, small modular reactor.

1 Introduction

Currently, uranium is considered as the base fuel material for all nuclear reactors in operation responsible for the production of electrical energy. However, only 0.711% of natural uranium contains the fissile isotope U-235, so an enrichment process is required, which entails a significant expense in the preparation of nuclear fuel.

On the other hand, it is known that there are uranium reserves worldwide for the next 100 years [1], making important to search for new fuel elements, thus being able to extend the peaceful use of nuclear energy, having the advantage of not emitting greenhouse gases. During the last years, Thorium has emerged as an alternate element to replace Uranium as a fuel in reactors. Although Th-232 is a fertile isotope, by absorbing a neutron it is possible to obtain the fissile material U-233. Equation (1) shows the process:

$$Th^{232}(n,)Th^{233} \xrightarrow{\mathrm{Q}^{-}(\boldsymbol{23\ min})} Pa^{233} \xrightarrow{\mathrm{Q}^{-}(\boldsymbol{27.4\ d\acute{\imath}as})} U^{233}. \tag{1}$$

One of the drawbacks of nuclear energy is the production of radioactive waste (minor actinides and fission products), mainly those with a long half-life; however, the use of thorium in the fuel matrix helps to reduce this problem since that, the absorption of many more neutrons is required for the production of heavy isotopes. For example, it takes seven neutrons for Th-232 to produce Pu-239, unlike U-238 which only requires one neutron.

Research into the use of Thorium as a new nuclear fuel has already begun. *Schaffer* [1] makes a description of how Thorium can be used as fuel. In the work of *Anantharaman et. al.* [2], explains how some thorium-based fuel assemblies were irradiated with the intention of reprocessing and separating U-233. In the work of *Ibrahim et. al.* [3] the feasibility of incorporating Thorium into a fast reactor was investigated, it was possible to burn 25.9 Tons of Plutonium from LWRs and 5 Tons of U-233 were generated.

On the other hand, small modular reactors (SMRs) are advanced reactors that have the capacity to produce approximately one third of the energy of a conventional reactor, about 300 MW [4]. Being small devices, they can be easily preassembled and transported. This is why it is important to analyze the behavior of these devices when incorporating Thorium as a fuel in conjunction with a fast neutron spectrum.

In this article, a neutron analysis for a homogeneous design of the active part of the core of a small modular reactor was carried out, thorium-based fuel was used and no moderator element was used, seeking to maintain a fast neutron spectrum. Follow-up was given to the criticality, the inventory of produced and spent masses as well as the fuel burnup.

2 Materials and Methods

The active part of the core of a modular nuclear reactor was modeled, using thorium - based fuel. The model was completely homogeneous, establishing an 80/20 ratio in the U/Th mixture. Figure 2 shows the layout of the model, as well as the dimensions used. No moderator material was used, with the intention of always maintaining a fast neutron spectrum, and thus contributing to the reduction of trans-uranium elements with high half-lives.

All the simulations were carried out in steady state maintaining a nominal power of 300 MWth. The operating temperature was established at 1200 K, with the intention of expanding the effective sections of neutron capture in the materials (Doppler Broadening [5]) and thus increase the nuclear transmutations. Liquid sodium was used as cooling material. Six burn steps were simulated for a total of 650 days of irradiation.

All the simulations were carried out by Monte Carlo technique, using the MCNP code, version 6.2 [6]. Two macro-bodies (cylinder and hexagonal prism) were used for the construction of the geometry. The neutron analysis focused on determining the k_{eff}, the fuel burnup and the building of the inventory of fission products and minor actinides. Table 1 shows the materials and their corresponding isotopes used in the simulations.

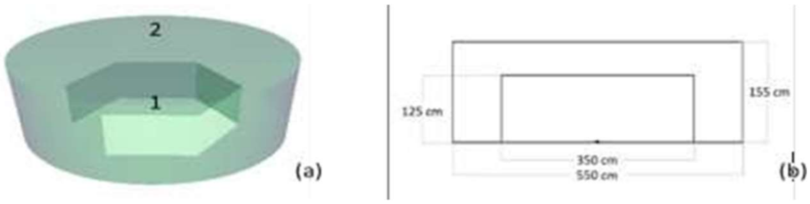

Fig. 1. (a) 3D view of the active part of the homogenous core; (1) is core and (2) reflector (b) Dimensions set in the model.

Table 1. Materials used in the simulated models.

Material configuration of the homogeneous core/reflector
Core
U-234, U-235, U-238 (primary fuel) 80%
Th-232 (secondary fuel) 20%
Si-28, Si-29, Si-30 (cladding)
C (fuel and cladding)
Na (refrigerant material)
Reflector
Zirconium Silicide ($Zr_3\ Si_2$)

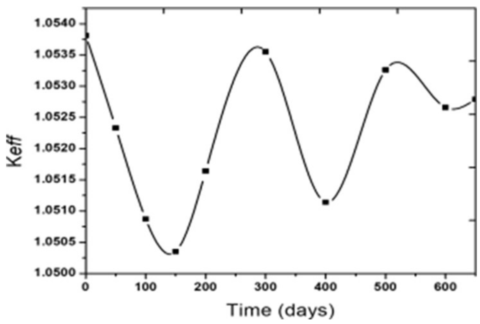

Fig. 2. Evolution of criticality throughout the irradiation period.

3 Results and Discussion

For the enrichment levels 5, 10 and 15% of U-235, the criticality values were 0.65, 0.85 and 0.92 respectively, producing a subcritical reactor; with 17% enrichment, supercriticality was reached. Figure 2 shows the temporal evolution of the k_{eff} for the entire simulated irradiation period. It can be noted how small oscillations occur over time but always maintaining a value greater than 1.0, therefore there is the assurance of constant energy production during this time.

Figure 3 shows the production and vanishes of the important actinides followed for 17% enrichment, a small amount of Np-237 was produced, an isotope with a half-life of 2.14×10^6 years and high radiotoxicity. There is no virtual production of actinides like americium and curium.

As for the plutonium isotopes, only Pu-239 was generated, which together with U-233 can contribute fission reactions and thus extend the reactor's operating cycle. The

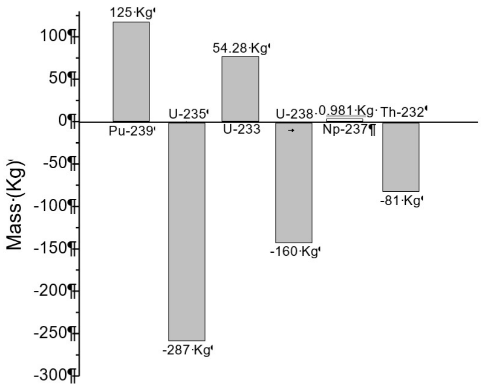

Fig. 3. Masses produced and consumed after the irradiation period.

fuel burnup for the entire irradiation period was 3.035 GWd/MTU, for all levels of enrichment, thus inferring that the use of fuel is independent of the level of enrichment.

4 Conclusion

According to the results obtained, the scenario with 17% enrichment was the ideal one, since supercriticality was obtained with it. Likewise, the incorporation of Thorium as a new fuel helped to generate the fissile material U-233, an element that could be used to maintain the fission reactions, or to be extracted through a reprocessing of the spent material, for later use in another reactor core.

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