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Layer thickness evaluation for transuranic transmutation in a fusion–fission system

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HIGHLIGHTS

- Layer thickness for transmutation in a fusion–fission system was evaluated.
- The calculations were performed using MONTEBURNS code.
- The results indicate the best thickness and volume ratio to induce transmutation.

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ABSTRACT

Layer thickness for transuranic transmutation in a fusion–fission system was evaluated using two different ways. In the first one, transmutation layer thicknesses were designed maintaining the fuel rod radius constant; in the second part, while the transmutation layer thickness increases, the fuel rod radius decreases maintaining k_s (source-multiplication factor) ≈0.95. Spent fuel reprocessed by UREX+ method and then spiked with thorium and uranium composes the transmutation layer. The calculations were performed using MONTEBURNS code (MCNP5 and ORIGEN 2.1). The results indicate the best thickness and the volume ratio between the coolant and the fuel composition to induce transmutation.

1. Introduction

Since all the actinides are potentially radiotoxic and since neutron capture (n,γ) reactions in these actinides just produce more actinides, the main effective way to reduce them is by neutron fission (n,f) reactions. Some of actinides are effectively not fissionable in a thermal neutron spectrum, such as the neutron spectra in almost all commercial nuclear reactors. In addition, it is known that the probability of fission per neutron absorbed is greater for all the actinides in a hard neutron spectrum (Stacey, 2007a). Therefore, the use of fast neutron produced in nuclear fusion reaction could increase the fission to capture ratio for the plutonium or the minor actinides (MAs).

Some systems have been proposed including fusion–fission hybrid, Gen IV reactor concepts and sub-critical systems ADS to induce transmutation in minor actinides and plutonium isotopes (Cardoso et al., 2012; Graiciany et al., 2012).

Previous works using fusion–fission hybrid reactor concept suggest a suitable position for the transmutation layer inside a TOKAMAK system with ITER dimensions (Velasquez et al., 2012a), as well as the importance of the neutron flux spectrum behaviour through the different walls and how it affects the material choice used in the first wall (FW) (Velasquez et al., 2012b, 2014). Giving continuity to these studies, it will be evaluated how the variations from the transmutation layer thickness and the fuel rod radius will influence in the transmutation and how it could be improved. In the first part, the fuel rod radius is maintained constant, and the transmutation layer thickness will be variable from 10 up to 25 cm depending on the case. In the second part, both will be variable, the fuel rod diameter and the transmutation layer thickness. These

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variations are made maintaining the k_s around 0.95. The material to be transmuted came from a PWR standard fuel (33,000 MWd/T burned),with 3.1% of initial enrichment left by 5 years in the pool (Cota and Pereira, 1997). The spent fuel was reprocessed by UREX method, then spiked with depleted uranium and spiked with thorium with 20% of fissile material. The evaluation will include the efficiency of transmutation of each layer to investigate which one is the best to achieve the transmutation.

2. Methodology

The system was simulated in MCNP5 (X-5 Monte Carlo Team, 2003) placing a transmutation layer inside the block shield. The depletion was performed using the MONTEBURNS code (Poston and Trellue, 1999), which links the MCNP5 with ORIGEN2.1 (ORIGEN2, 1980). The neutron flux over the fuel obtained from the MCNP5 output is used for the ORIGEN2.1 to perform the burnup. Then the isotopic composition obtained by the ORIGEN2.1 goes back to the MCNP5 to calculate the flux with a new composition submitted to the fusion neutron source and so on until finishing each cycle.

Currently, two parameters are being frequently used as the index of the subcriticality level of the hybrid system; one of them is the conventional effective multiplication factor k_{eff}, and the other is so-called source-multiplication factor k_s. The neutron source multiplication factor of a subcritical assembly driven by an external neutron source can be expressed as the ratio between the fission neutrons and the fission neutrons plus the neutrons from the source. The k_s factor is defined as the ratio of neutron production to loss for a subcritical system just, in the same way for k_{eff}. Physically, k_s denotes the degree of multiplication of the external source, while k_{eff} indicates the multiplication of the fission neutrons (Hill et al., 2002). The MONTEBURNS code uses the source definition calculated in Eq. (1) obtained from the value of the net multiplication obtained from the MCNP output file:

$$k_s = \frac{(f_{\text{mult}} - 1)}{(f_{\text{mult}} - 1/\upsilon)} \quad (1)$$

where f_{mult} is the total neutron multiplication factor of the system and υ is the ratio of the source neutrons to the neutron lost to fission (X-5 Monte Carlo Team, 2003; Poston and Trellue, 1999).

In a hybrid system, such as the fusion–fission reactor, is important to define the subcriticality levels consistently in order to maintain the system security during the irradiation time.

2.1. Geometry model

The geometry uses the intersection of cylinders and planes to delimit boundaries of the transmutation layers, as well as the fusion device. This geometry was chosen due to its simplicity, its low relative error. Furthermore, it allows simulating part of the device individually. Fig. 1 shows a 3D fusion–fission reactor with the transmutation layer. The transmutation zone starts at the beginning of the block shield at 856 cm. The thickness will be modified depending on the studies. In the first study, the fuel rod radius is maintained constant, and there are just variations on the thicknesses. In the second study, the fuel rod radius decreases while increasing the transmutation layer thickness. The geometry in the xy axis is shown in Fig. 2 where the transmutation zone is within the red mark. The transmutation zone is filled with a hexagonal lattice containing the fuel rods and the coolant.

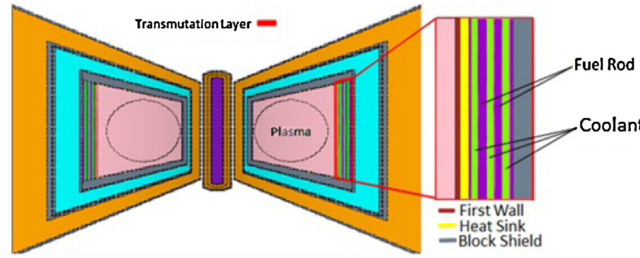

Fig. 1. Part of the geometry in the xz axis showing within the red mark where is located the transmutation zone. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

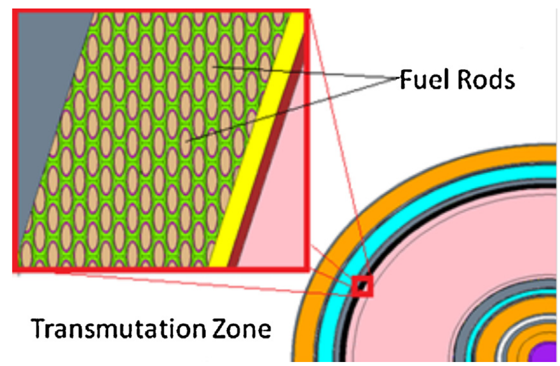

Fig. 2. Quarter top of view from the TOKAMAK showing in details the transmutation zone and the fuel rods between the heat sink and the block shield. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In the first part, it was performed three calculations for the reprocessed fuels spiked (RFS) with thorium, and spiked with depleted uranium. The goal is to compare the transmutation achieved for different values of the source multiplication factor. The main difference between these fuels is that the fuel spiked with uranium has higher values of k than the fuel spiked with thorium. Therefore, the thickness of the transmutation layer for the fuel spiked with thorium has higher values. The performed calculations were the same for both fuels in which it was maintained constant the fuel rod radius at different transmutation layer thicknesses. For uranium, the thicknesses were 10, 15 and 20 cm with a fuel rod radius of 0.8 cm and for thorium, the thicknesses were 15, 20 and 25 cm with a fuel rod radius of 0.81 cm. Table 1 shows an example of proportion of each transmutation layer used for both fuels. All the models have a height of $h \approx 476.7$ cm. The volume ratio of coolant to the fuel for each case is maintained almost constant about $V_{\text{coolant}}/V_{\text{fuel}} \approx 0.457$. The total fission power established for this first part was 2200 MW. The maximum fusion power is 311 MW.

In the second part, the fuel rod radius was changed according to the thickness of the transmutation layer to achieve an initial

Table 1
Transmutation layer thicknesses and fuel rod radius.

Transmutation layer					
RFS with uranium Fuel rod radius 0.8 cm			RFS with thorium Fuel rod radius 0.81 cm		
10 cm	15 cm	20 cm	15 cm	20 cm	25 cm