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Effect of Spectral Shift on Conversion Ratio in $(Th\text{-}^{233}U)O_2$ Fuel

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Abstract

Spectral shift principle was applied to modify resonance absorption in ^{232}Th in a $(^{232}Th\text{-}^{233}U)O_2$ fueled model of the Czech research LR-0 reactor. The aim was to obtain the best fuel utilization by varying the ratio of D_2O/H_2O in the moderator. MCNP code was used to model the LR-0 reactor. 11 different D_2O / H_2O mixtures viz.; 0%, 10%, …., 90%, 100% D_2O were investigated. Conversion ratio of ^{232}Th to ^{233}U was maximal at 100% D_2O.

Keywords: Spectral shift; heavy/light water mixtures; conversion ratio; $Th\text{-}^{233}U$ oxides fuel.

1. Introduction

Spectral shift of neutron flux in thermal nuclear reactors can be achieved by varying D_2O/H_2O ratio in moderator as mixed water moderator. A previous study on LR-0 reactor fueled by UO_2 showed that best conversion ratio was obtained at about 90% heavy water ratio in moderator, followed by slight spectral softening to 100% D_2O [1].

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For (^{232}Th-^{233}U)O_2 fuel; neutron capture cross section of Thorium is slightly different from that of ^{238}U. Hence, it can be anticipated that maximum conversion ratio in a (^{232}Th-^{233}U) O_2 fuel will be obtained at some mixed water moderator ratio other than the 90% D_2O obtained by authors of [1]. Our research was investigating this optimum D_2O/H_2O %.

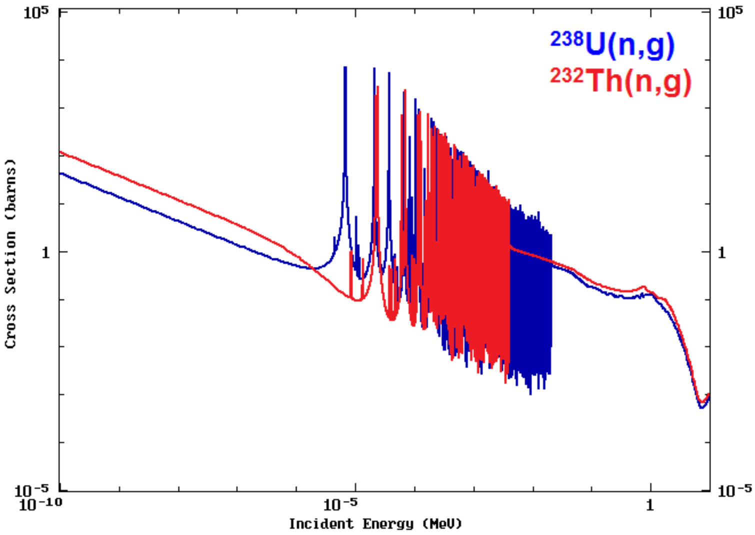

Figure 1: Neutron capture cross sections of ^{238}U, and ^{232}Th [2]

Figure 1 presents the neutron capture cross sections of ^{238}U, and ^{232}Th [2]. It shows heavy resonances over the epithermal energy range in both nuclides. It can also be seen that neutron capture resonances in ^{238}U cover wider range of the epithermal energies than do ^{232}U. Therefore, it can be estimated that conversion ratio in (^{232}Th-^{233}U)O_2 fueled reactor will be less sensitive to spectral hardening than do a UO_2 fueled reactor.

Authors of [1] found that the greatest spectral hardening in a UO_2 fueled reactor was obtained at 90% D_2O/H_2O mixture, but the spectral shift were very small. Yet, inspecting ^{232}Th neutron capture cross section, we can see that its neutron capture resonances start at much higher energies than those of ^{238}U neutron capture. Therefore, it worth investigation whether a (^{232}Th-^{233}U)O_2 fueled nuclear reactor will similarly show maximum conversion ratio at 90% D_2O/H_2O, or will its more energetic epithermal neutron capture resonances will make it un-sensitive to the slight spectral softening from 90% D_2O/H_2O mixture to 100% D_2O moderator.

11 different D_2O / H_2O mixtures viz.; 0%, 10%, …., 90%, 100% D_2O were investigated as moderator in an MCNP5 model of LR-0 reactor (a czeck light water zero power research reactor) if it were fueled by (^{232}Th-^{233}U)O_2 fuel. For each D_2O%, conversion ratio was calculated.

2. Materials (*LR-0 Model*) [3]

In the present study, the LR-0 reactor core model was assembled of 13 fuel assemblies see figures 2, 3.

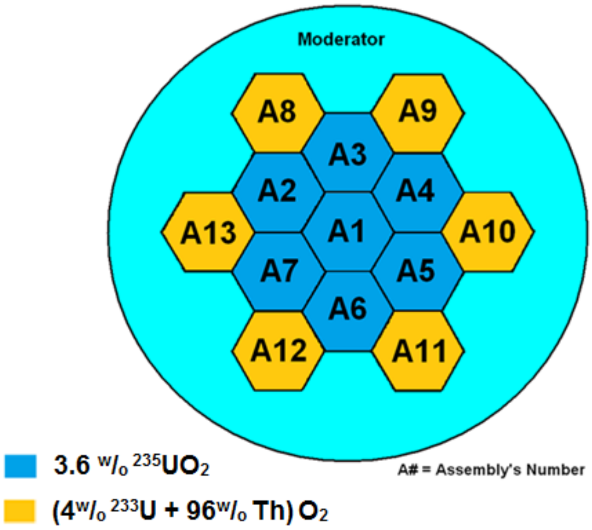

Figure 2: Fuel assembly numbering and core configuration

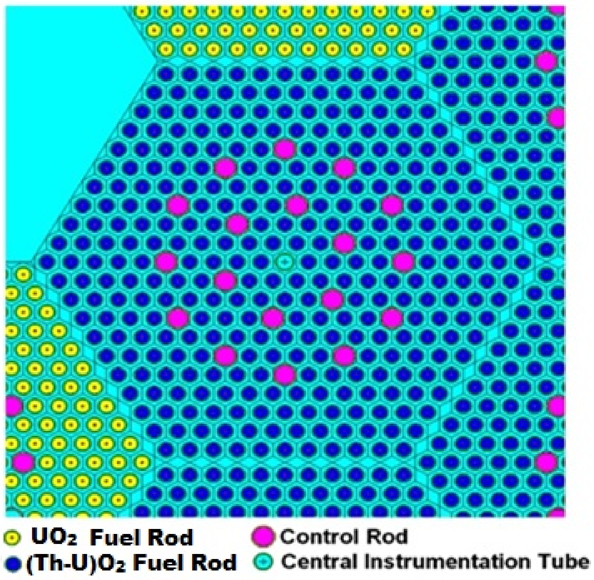

Figure 3: Structure of fuel assembly

2.1. Fuel pins structure

Files Fuel in assemblies number 1–7 is UO_2 of enrichment = 3.6 $^{w}/o$ and density = 10.32 g/cm^3. Fuel in assemblies number 8–13 is (^{232}Th-^{233}U) O_2 have enrichment = 4 $^{w}/_{o}$ for ^{233}U and 96 $^{w}/_{o}$ for ^{232}Th, and density = 9.52 g/cm^3.

2.2. Control rods

To change reactivity; the control rods were not (as in real reactors) withdrawn out of core rather they were shortened or elongated inside the core. This was meant to avoid disturbing the neutronic properties of the moderator in the upper plenum. All Boron was assumed to be ^{10}B as its very high neutron absorption cross section allowed the reactor model to be critical with the control rods partially inserted in all of the study cases (see figure 3).

2.3. Moderator

The moderators used in the present study were 11 different mixtures of heavy/light waters at molecular ratios of D_2O of 0%, 10%, 20%, . . ., 100%. The moderator filled the model and had an outer shape of a square cylinder with 250 cm in diameter and height, symmetrically surrounding the reactor core (see figure 4).

Structural components of the reactor e.g. reactor vessel, assembly spacing grids and bottom structures were neglected in the model for simplicity and since their neutronic influences are unwanted for comparing the nuclear properties of mixed water moderators having different molecular ratios of D_2O.

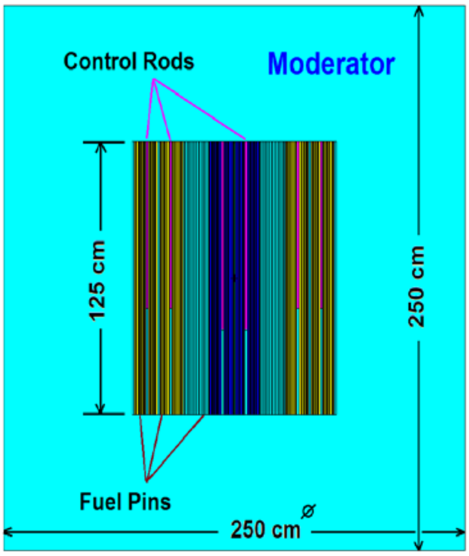

Figure 4: Reactor Layout

3. Methods

3.1. Code

MCNP5 was used to model the LR-0 reactor and carry out the study. The reactor was assumed to be at room temperature and atmospheric pressure.

3.2. Tallies

Neutron energy was classified into 3 groups [4]; viz. thermal (< 1 eV), epithermal (1 eV–0.1 MeV), and fast (> 0.1 MeV). For each of the 11 studied heavy/light water mixed moderator cases; the tallies included neutron spectrum and neutron capture rate in the (^{232}Th-^{233}U) fuel cells.

4. Results

The 11 models of the LR-0 reactor were set to criticality (k_{eff} =1.00000, with tolerance of +0.00051) by changing the lengths of the B_4C control rods. Table 1 presents the multiplication factors of the 11 models.

Table 1: k_{eff} and relevant statistical data for the 11 studied LR-0 models

LR0	LR10	LR20	LR30	LR40	LR50	LR60	LR70	LR80	LR90	LR100	
D_2O%	0	10	20	30	40	50	60	70	08	90	100
k_{eff}	1.00036	1.00047	1.00046	1.00010	1.00017	1.00039	1.00026	1.00010	1.00045	1.00031	1.00038
S. D.	0.00049	0.00048	0.00047	0.00047	0.00052	0.00047	0.00050	0.00051	0.00050	0.00049	0.00079

4.1. Neutron Spectra in the (Th-U) fuel

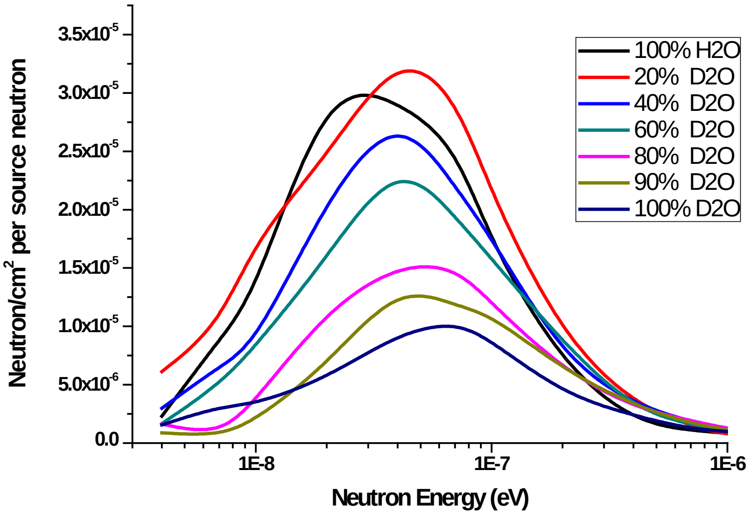

Figure 5: Spectral shift in ^{232}Th-^{233}U fuel at different D_2O%

Figure 5 shows that neutron spectrum in ^{232}Th-^{233}U fuel was hardened with increase of D_2O% in moderator. This agrees with the finding of authors in [1].

4.2. Epithermal Neutron Flux in ^{232}Th-^{233}U Fuel Cells

Neutron capture cross section in ^{232}Th is mainly at epithermal energies. Epithermal neutron flux in ^{232}Th at different D_2O% is presented in figure 6.

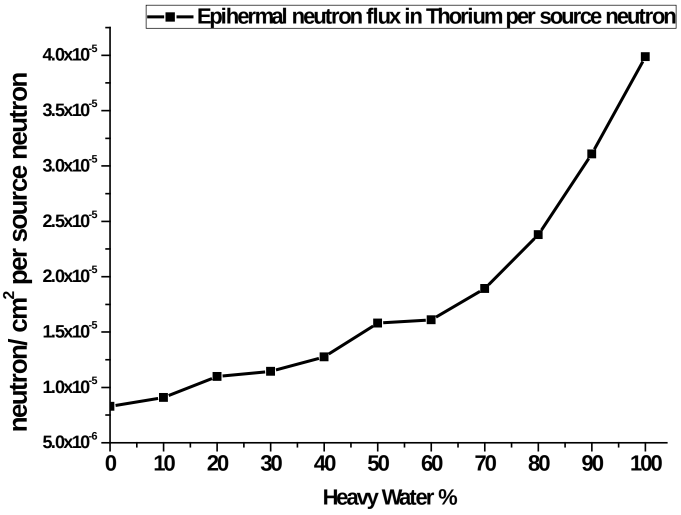

Figure 6: Epithermal neutron flux in ^{232}Th-^{233}U fuel cells at different D_2O%

Epithermal neutron flux in ^{232}Th-^{233}U fuel increased almost exponentially with increasing D_2O% in moderator. This agrees with the overall spectral hardening with increasing D_2O% in moderator.

4.3. Neutron Capture in ^{232}Th

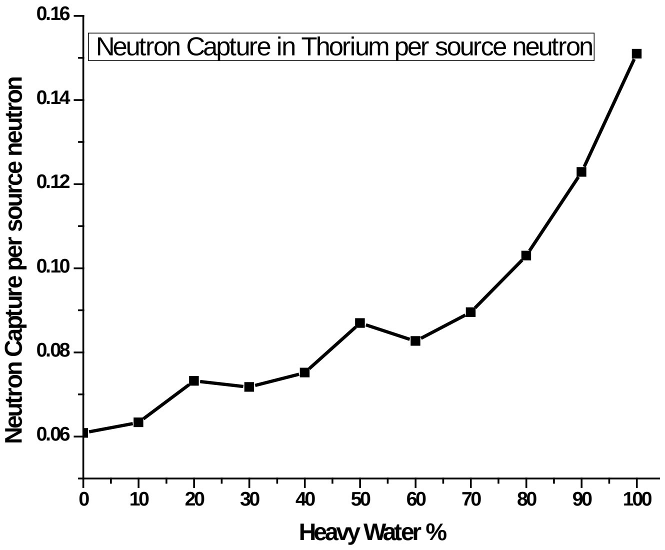

Figure 7: Neutron capture in ^{232}Th at different D_2O%

Neutron capture rate in ^{232}Th increased exponentially with increasing D_2O% in the moderator (see figure 7).

Since ^{232}Th neutron capture cross section is high at epithermal energies [5], neutron capture rate in ^{232}Th is proportional to epithermal neutron flux in fuel which increases with increase of D_2O%.

4.4. Conversion Ratio

Figure 8 shows that conversion ratio was greatest at 100% D_2O moderator. This was expected from the neutron capture rate curves (figure 7).

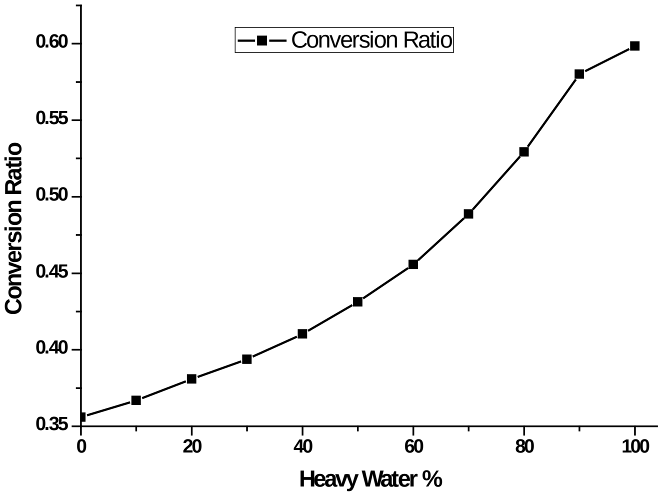

Figure 8: Conversion ratio at different D_2O%

5. Discussion

Neutron capture in ^{232}Th is mainly epithermal, hence; conversion ratio is expected to increase as the neutron spectrum is getting harder, i.e. as the most probable neutron energy becomes greater than thermal energy. According to the results obtained in the present research, it was found that as heavy water percentage was increased in moderator, spectrum in the ^{232}Th-^{233}U fuel was hardened, with an accompanying increase of epithermal neutron flux. This caused an increase of neutron capture rate in ^{232}Th, increasing the generation rate of ^{233}U. As a result, conversion ratio was increased.

In a previous research, authors in [1] found that for UO_2 fueled LR-0, spectral hardening and conversion ratio were maximal at 90% D_2O, then it decreased between 90% and 100% heavy water percentage. In our present work; it was found that for ^{232}Th-^{233}U fueled LR-0, spectral hardening and conversion ratio continued to increase from 0% till 100% heavy water percentage. However, it was noted that between 90% and 100% heavy water percentage, the rate of increase of conversion ratio was markedly decreased. This implies that neutron capture cross section of the fuel ingredients is crucial in reactor's neutronic behavior in general, and in heavy water percentage that will provide maximum conversion ratio in particular. This re-addresses the worth of spectral shift principle [6,7] to get the greatest possible burnup rate from nuclear fuels.

6. Conclusions

Applying spectral shift principle by varying D_2O% in the moderator influences the neutrons interaction rates with fuel, including neutron capture rate. For $(^{232}Th\text{-}^{233}U)O_2$ fuel, maximum conversion ratio was obtained at 100% D_2O moderator. This suggests that using 100% heavy water moderator for $(^{232}Th\text{-}^{233}U)O_2$ fueled nuclear reactors, may provide greater burnup rate and/or longer core life.

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