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Neutron absorption profile in a reactor moderated by different mixtures of light and heavy waters

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ABSTRACT

A Monte-Carlo parametric study was carried out to investigate the neutron absorption profile in a model of LR-0 reactor when it is moderated by different mixtures of heavy/light waters at molecular ratios ranging from 0% up to 100% D_2O at increments of 10% in D_2O. The tallies included; neutron absorption profiles in control rods and moderator, and neutron capture profile in ^{238}U. The work focused on neutron absorption in control rods entailing; total mass of control rods needed to attain criticality, neutron absorption density and total neutron absorption in control rods at each of the studied mixed water moderators. The aim was to explore whether thermal neutron poisons are the most suitable poisons to be used in control rods of nuclear reactors moderated by mixed heavy/light water moderators.

1. Introduction

Earlier studies of the mixed heavy/light water moderator of nuclear reactors showed that the neutron spectrum in a reactor is hardened as the percentage of heavy water in its moderator increases (Wehmeyer et al., 1962; Barrett et al., 1962; Tochihara et al., 1998; Nagy et al., 2014). An earlier work of the authors (Nagy et al., 2014) on the neutronic behavior of a nuclear reactor moderated by different mixtures of heavy/light waters showed that the total mass of control rods needed to attain criticality in reactor did not linearly decrease with increase of the heavy water percentage in moderator. This non-linearity was presumed to be due to the neutron spectral shift, that called for further exploration of the neutron absorption profile in control rods at different mixed heavy/light water moderator mixtures.

Thermal neutron poisons are conventionally used in control rods of thermal nuclear reactors since the neutron spectra in these reactors are thermal. However; as the neutron spectra in mixed water moderated reactors are hardened with increase of heavy water percentage in moderator, it is presumed that neutron poisons other than the thermal poisons might be more suitable for control of those mixed water moderated reactors. To verify this assumption; the neutron absorption profiles in control rods of a nuclear reactor moderated by 11 different mixtures of heavy/light waters were studied. For further understanding of the results, the neutron capture spectra in ^{238}U and neutron absorption spectra in moderator were also tallied.

The current work is an MCNP5 parametric study of the neutron absorption profiles in control rods and in moderator, and of neutron capture profiles in ^{238}U in LR-0 reactor when it is moderated by mixtures of heavy/light water at molecular ratios ranging from 0% up to 100% D_2O at increments of 10% in D_2O. The neutron absorption spectra are presented in 3 groups (viz. Thermal, epithermal, and fast). Total mass of control rods, neutron absorption density, and total neutron absorption in control rods were also tallied for each of the 11 studied heavy/light mixed water moderators.

2. Material and methods

2.1. LR-0 Model

LR-0 is a Czech experimental light-water-moderated zero-power reactor, originally designed for the research of VVER-1000 and VVER-440 type reactor cores (VVER = *Vodo-Vodyanoi Energetichesky Reactor*; *Water–Water Energetic Reactor*, the Russian Pressurized Water Reactor) and benchmark experiments. The LR-0 fuel assemblies are shortened VVER assemblies (125.0 cm in LR-0, 355.0 cm in VVER). The LR-0's continuous maximal nominal power

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is 1 kW with thermal neutron flux $\approx 10^9$ n/cm^2 s. In the present study, the LR-0 reactor core model was assembled of 13 fuel assemblies of two different enrichments (4.4 ^{w}/o, 3.6 ^{w}/o in ^{235}U). Each fuel assembly is hexagonal in shape of radius = 13.60 cm and is 125.0 cm long. Each assembly is divided into 331 hexagonal moderator cells; each of radius = 0.736 cm. Each fuel assembly contains 312 fuel pins, 18 cluster tubes, and 1 central instrumentation tube. The 18 cluster tubes were arranged according to the standard LR-0 reactor fuel assembly (Kyncl et al., 2005) (see Figs. 1–3).

2.1.1. Fuel pins

Each fuel pin is 125.0 cm long. It is a hollow cylindrical with 1.4 mm inner diameter, and 7.53 mm outer diameter. It is encased inside a clad tube 0.735 mm thick. The axial hollow space is filled with helium gas. The gap between the fuel and the clad is neglected in the model. The fuel is UO_2. Fuel assemblies number 1–7 have enrichment = 3.6 ^{w}/o, at mass density = 10.32 g/cm^3. Fuel assemblies number 8–13 have enrichment = 4.4 ^{w}/o, at mass density = 10.08 g/cm^3. The clad material is ZrNbHf alloy at density = 6.45 g/cm^3 (see Fig. 4).

2.1.2. Cluster tubes

Cluster tubes are made of stainless steel, with inner diameter of 11.0 mm, and outer diameter of 12.6 mm. They contain the control rods (see Fig. 5).

2.1.3. Control rods

Control rods are made of B_4C. They are cylindrical with 11.0 mm diameter. The control rods were grouped into 3 groups; the first group in central fuel assembly, the second group in fuel assemblies number 2–7, and the third group in fuel assemblies number 8–13. Each group of control rods is moved together independent of the other groups. For changing reactor reactivity; the control rods were not (as in real reactors) inserted in/or withdrawn out of core, rather they were lengthened or shortened within the core. This was meant so as not to disturb the neutronic properties of the moderator outside the core. All boron was assumed to be ^{10}B, as its very high neutron absorption cross section allowed small changes in control rods lengths to change significantly the criticality of the reactor. This allowed attaining criticality at all of the 11 studied heavy/light moderator mixtures (see Fig. 5).

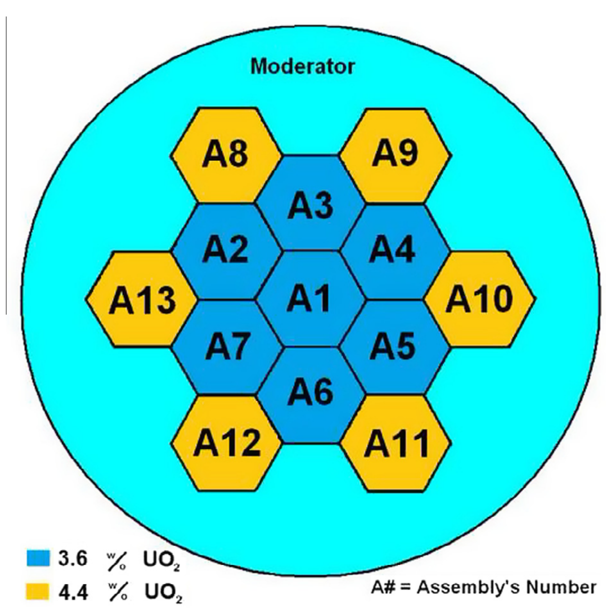

Fig. 1. Fuel assembly numbering, core configuration and fuel enrichment distribution.

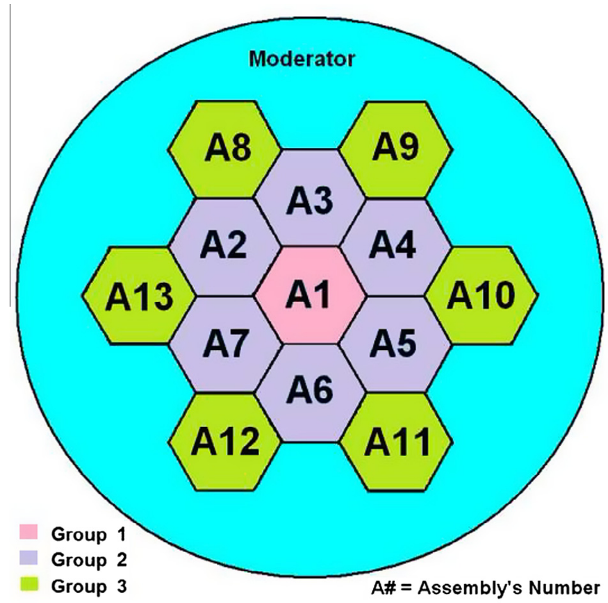

Fig. 2. Control rods groups.

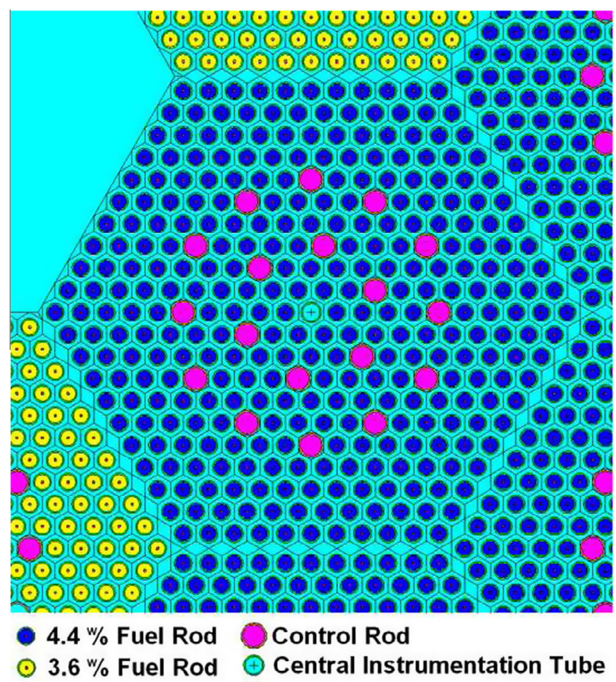

Fig. 3. Structure of a fuel assembly.

2.1.4. Central instrumentation tube

The central instrumentation tube is made of ZrNbHf alloy, with inner diameter of 8.8 mm, and outer diameter of 10.25 mm. It is filled with moderator (see Fig. 5).

2.1.5. 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 – with