THE BURNUP INFLUENCE ON THE INTEREST PARAMETERS OF A CANDU LATTICE WITH NATURAL AND SLIGHTLY ENRICHED URANIUM

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ABSTRACT

The paper goal is to find out the burnup influence on lattice parameters of interest when nuclear fuels with Natural Uranium (NU) and Slightly Enriched Uranium (SEU) are used. The considered lattice parameters consist of the infinite multiplication factor and the isotopic contribution to the fission power for some of the major actinides such as Uranium and Plutonium. The widely spread transport equation solver computer code WIMS (Winfrith Improved Multigroup Scheme) was used. The working configurations correspond both to fresh and to irradiated nuclear fuel up to the discharge burnup from a generic CANDU power reactor. Three Uranium enrichments were used: 0.72 w% U235 (corresponding to the Natural Uranium), 1%w U235 and 2%w U235 corresponding to the SEU fuel. The unique critical (discharge) burnup values are also presented for every of the three enrichments. The results showed that almost one and a half discharge burnup can be obtained using a nuclear fuel with a quite light enrichment of 1%w U235, while 2%U235 configuration is able to supply almost three times larger discharge burnup. The peculiar individual fissile actinides' contributions to the total fission power with respect to enrichments and burnups are also discussed.

Key words: WIMS, Natural Uranium, Slightly Enriched Uranium, fission power

Introduction

CANDU (CANada Deuterium Uranium) is the widest pressure tubes reactor in operation around the world. CANDU is heavy water moderated and cooled reactor using Natural Uranium fuel in a simple a simple and flexible fuel bundle design. With two nuclear units in operation at Cernavoda NPP, Romania should be interested in the use of advanced fuel cycles in actual CANDU power reactors. The goal of our work is to find out the burnup influence on lattice parameters of interest when nuclear fuels with Slightly Enriched Uranium (SEU) are used, compared to the case of Natural Uranium (NU). The lattice parameters pursued in calculations were the infinite multiplication constant and the contribution to fission power of some major actinides such as: Uranium-235, Uranium-238 along with Plutonium series (Pu-239, Pu-240, Pu-241 and Pu-242).

Methodology Outlines

The methodology used in the paper is based on performing neutron lattice calculations to solve the transport equation using the WIMS computer program [1] and its updated public library, [2] supplied by the International Atomic Energy Agency (IAEA). The transport equation models the behavior of neutron population inside of nuclear system. The WIMS program allows to calculate a lot of lattice interest parameters. We pursued the infinite multiplication constant and the contribution to the total fission power brought by the major actinides alluded in introduction.

The fuel composition, the bundle design, the working configurations and the main WIMS region radii are synthesized in Table 1. Three enrichments for nuclear fuel placed in the standard 37-rods CANDU bundle were used: 0.71, 1.0 and 2% mass percent of U235. Fig. 1 presents the CANDU 6 elementary lattice [3].

Table 1. *The working configurations*

Configuration Name	**NU**	**SEU1%**	**SEU2%**
Config. #	1	2	3
Enrichment %U235	0.71	1.0	2.0
Number of rods per fuel ring	CE=1, R1=6, R2=12, R3=18		
Bundle Geometry	CANDU 37-rods (CANDU standard)		
Total Uranium mass (kg)	19.9		
Total fuel mass (kg)	22.6		
Total Zircaloy mass (kg)	2.15		
Total bundle mass (kg)	24.74		
Pressure Tube Internal Radius, [4]	5.17 cm		
Pressure Tube External Radius (ANNULUS 5), [4]	5.6 cm		
Annular Gas Thickness, [4]	0.85		
Calandria Tube Internal Radius (ANNULUS 6), [4]	6.45 cm		
Calandria Tube External Radius (ANNULUS 7), [4]	6.59 cm		
Lattice Pitch (ANNULUS 8), [4]	28.575		

*CE = Central Element; R1,R2,R2=inner rings from CE to outside, see Fig. 1

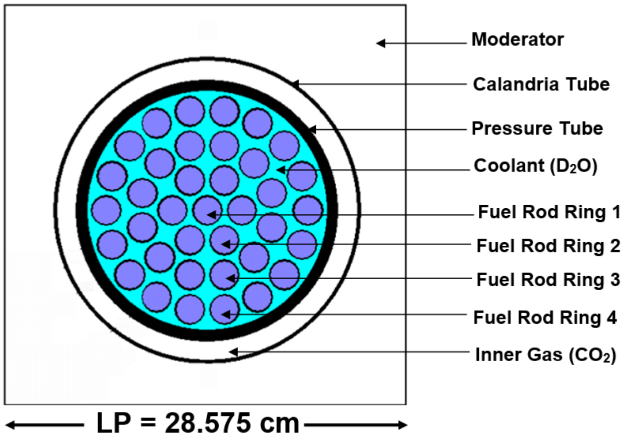

Fig. 1. *The CANDU elementary lattice, [3]*

The data regarding CANDU lattice dimensions was taken from public domain [4], while the fuel and zircaloy masses were calculated supposing a density of 10.5 g/cm^3 for fuel and an equivalent density of 7.5 g/cm^{3}for zircaloy alloy. In the WIMS model we supposed that the entire mass of zircaloy is distributed around the fuel rods in the clad. As result, the zircaloy density should be increased from 6.5 g/cm^3 to 7.5 g/cm^3 in order to preserve its total bundle mass. Fig. 2 illustrates the WIMS model built with the main 8 regions (identified in the input data file by the keyword "*ANNULUS*").

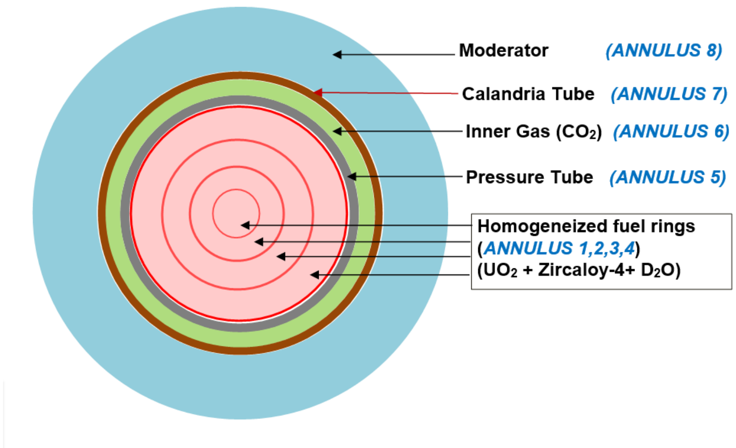

Fig. 2. *The WIMS model for the CANDU elementary lattice*

Instantaneous burnup calculations have been performed in order to find out the exit discharge (critical) burnups i.e. those burnup values for which the lattice is still critical. The major actinides contribution to fission power with respect to the fuel burnup were also pursued. The "*REACTION*" keyword was used to specify all the actinide isotopes possible to have contribution to fission power. They are denoted firstly by the order number, then the periodic table symbol and lastly, by their atomic mass as following: 92-U-233, 92-U-235, 92-U-236, 92-U-238, 94-Pu-238, 94-Pu-239, 94-Pu-240, 94-Pu-241, 94-Pu-242. Despite the fact that the initial fuel composition only included 92-U-235 and 92-U-238 isotopes, the final output files reveal the presence of all above mentioned isotopes.

The fission power is that power released only from fissions underwent by fissile isotopes. It is generally known that a fission reactor works using Uranium as fuel, but it seems usually to be less known the contribution to fission power of other heavy isotopes generated by nuclear reaction during the fuel burning process. In order to capture the contributions and their share in the total fission power we took these values from WIMS output file sections' entitled "*0element isotope# reactions*", where the "*isotope#"* key word denotes the isotope identification number in the WIMS library.

The infinite multiplication constant *k-inf* is plotted under "*diagonal transport corrected flux solution*" WIMS output file section for every set of 45 MW/tU x 11.11 days burnup interval. The paper's results are presented and discussed below.

Results and discussions

In Table 2 the discharge burnup values are presented for every of the three configurations.

Table 2. *The discharge Burnups supplied by WIMS calculations*

Configuration Name	**NU**	**SEU1%**	**SEU2%**
Config.#	1	2	3
Discharge Burnup (MWd/kgU)	6.5	10.5	21.5

The *discharge burnup* can rapidly be discovered by plotting the infinite multiplication factor (sometimes referred as *the infinite reactor multiplication constant*, [3]) with respect to the burnup, as in Fig. 3. It is a measure of the total fission energy released by the nuclear fuel during its residence in the reactor core.

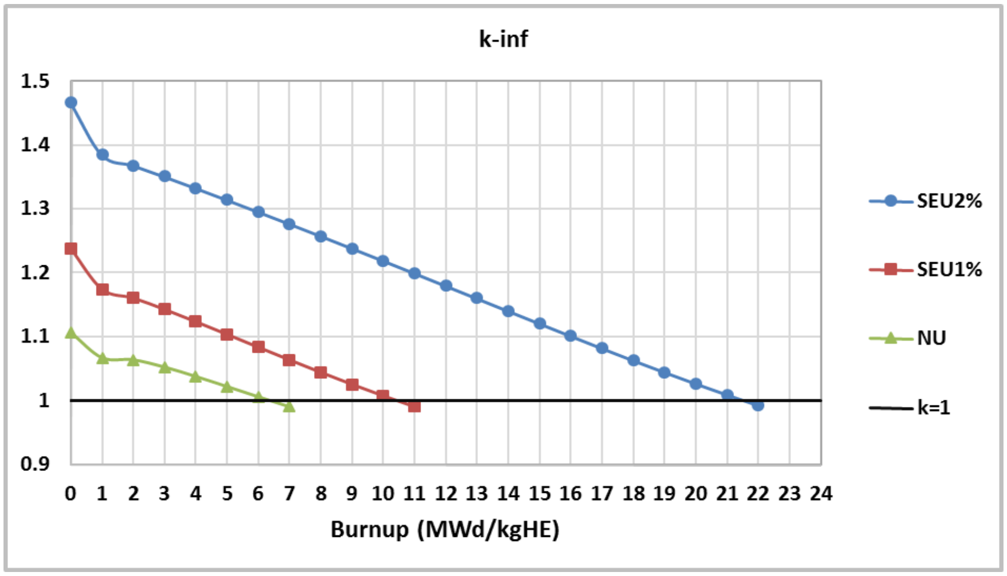

Fig. 3. *The infinite multiplication factor by fuel burnup*

The discharge burnup value corresponds to an infinite multiplication reactor constant of unity, when the initial reactivity excess has been exhausted and the fuel should be removed from the core. As it can be observed, an increase by 0.3% in the fuel enrichment (from 0.7 to1%) is able to produce 61% more energy from every kilogram of Uranium. Moreover, adding another one percent to the enrichment supplied 21.5 MWd/kgU as discharge burnup, almost three time more than in the case of Natural Uranium. Knowing that the radioactive waste amount is inverse proportional to the discharge burnup, we expect to have benefits regarding radioactive waste amount reducing by the same order along with a lower usage of the refueling machine.

The fissile isotope share into the total fission power is represented with respect to the fuel burnup in Figs. 4, 5 and 6.

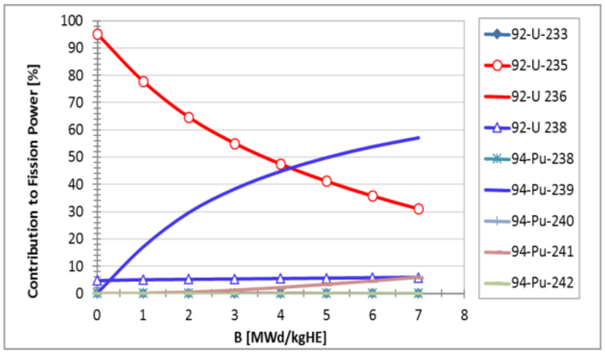

Fig. 4. *NU Contribution to the fission power*

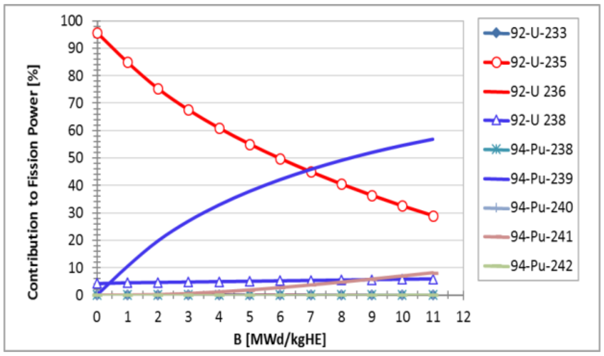

Fig. 5. *SEU1% Contribution to the fission power*

Despite the fact that the fission power share evolutions in Figs. 4, 5 and 6 seems to be very close each other, some differences can be disclosed representing the contribution of a single interesting fissile isotope for every of the three configurations in the same picture, as in Figs. 7 to 10.

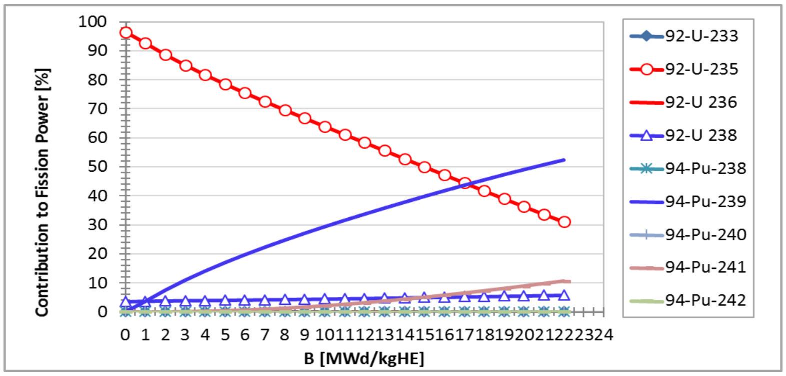

Fig. 6. *The SEU2% contribution to the fission power*

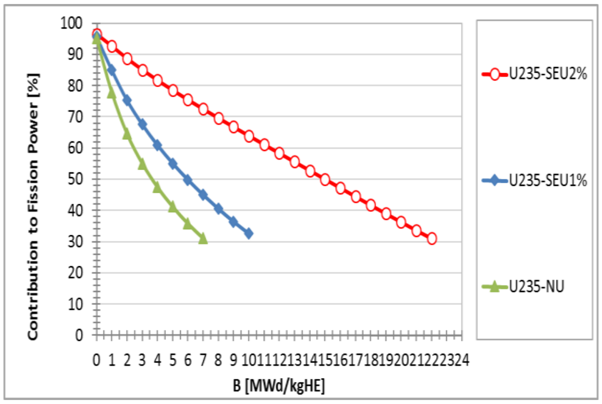

Fig. 7. *The **U-235** contribution to the fission power*

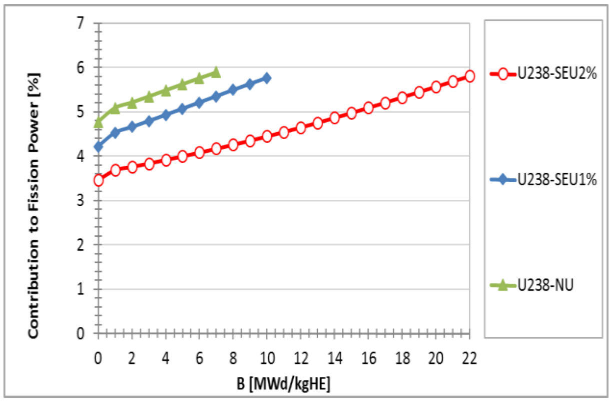

Fig. 8. *The **U-238** contribution to the fission power*

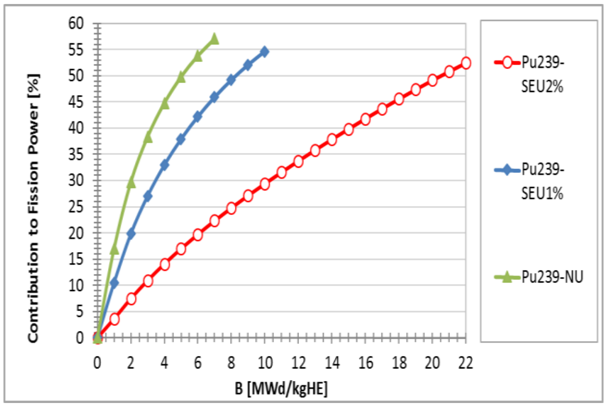

Fig. 9. *The **Pu-239** contribution to the fission power*

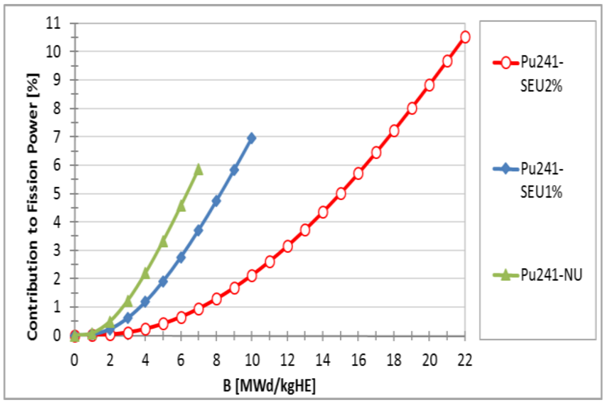

Fig. 10. *The **Pu-241** contribution to the fission power*

In Figs. 7, 8, 9 and 10 the contribution to the fission power of the main contributors is illustrated. The main contributors are: 92-U-235, 92-U-238 94-Pu-239 and 94-Pu-241. The rest of contributions (supplied by Pu-240 and Pu-242) are insignificant and therefore have not been represented.

Figures 5, 6 and 7 reveal that the most important contribution to the fission power is brought by the two fissile isotopes, namely U235 and Pu239, the first one being found "*as is*" in the natural Uranium ore while the second one being generated in the reactor during the burning process through nuclear reactions. While the U235 contribution decreases by burnup, the Pu239 contribution increases with respect to the fuel burnup. The equilibrium state, when the two contributions are equal takes place at a farther and farther time from the middle burnup moment, as follow: for the NU configuration the moment is 88.8 days (when the corresponding burnup is 4 MWd/kgU = 0.045 MW/kg*88.8 days, see Fig. 4), for the

SEU1% configuration the moment is 155.6 days (when the corresponding burnup is about 7 MWd/kgU = 0.045 MW/kg*155.6 days, see Fig. 5) and for the SEU2% configuration the moment is 377.8 days (when the corresponding burnup is about 17 MWd/kgU = 0.045 MW/kg*377.8 days, see Fig. 6).

In Fig. 7 the U235 contribution to the fission power with respect to the burnup is presented for every of the three configurations considered in the study. As it was expected, the U235 contribution decreases by the fuel burnup and it is greater at higher initial enrichments. Near the discharge burnup, the U235 isotope only contributes by 30% to the fission power.

Of interest is the contribution brought by U238 isotope which is usually less investigated. We can notice that 3 to 6% of the fission energy is released by fast fissions in U238 whose contribution slowly increases by burnup and as U235 is being consumed.

The Plutonium 239 contribution is revealed in Fig. 9 while that of Plutonium 241 is shown in Fig. 10. Being generated by two subsequent beta decays of U-238 isotope, the Pu239 contribution to fission power is direct proportional to the instantaneous concentration of its precursors, U238 and Neptunium-239. The Pu-239 contribution overrides fifty percents near the discharge burnup, see Fig. 9, being therefore, after U235, the most important contributor to the fission energy generation. Also, the odd atomic mass number Pu241 isotope reveals its significant contribution to the fission power in Fig. 10. This contribution rises up to 6, 7 and 10.5% with respect to the corresponding discharge burnups of the working configuration.

Conclusions / Remarks

The fissile and fissionable isotopic share to the total fission power has been revealed for a CANDU lattice fuelled with Natural and Slightly Enriched Uranium by using the WIMS burnup calculations.

Tracking the infinite multiplication factor variation with respect to the burnup, the unique discharge burnup values for every analyzed fuel configuration were found out.

Peculiar and less frequently investigated aspects regarding fissionable isotope contributions to the fission power have also been revealed.

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