CANDU NUCLEAR FUEL PERFORMANCE IMPROVING BY USING BUNDLES WITH MORE THAN 37 ELEMENTS

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Abstract

The paper evaluates neutronic performances of an advanced CANDU fuel bundle design with an Increased Number of Elements (INE) and fuelled with Natural Uranium (NU). Comparative lattice calculations have been performed both for the INE bundle design and the 37-rods standard fuel bundle design (STD). The two bundle designs are referred as INE and STD, respectively. The lattice results allow for the ring power distribution analysis and they showed that inside of the outermost of elements of INE design a lower thermal power is generated than in the case of the STD fuel bundle. Also, the outer element linear powers of the INE bundle design are lower than corresponding values supplied by the STD bundle design. Results from time-average core calculations are also presented and these show a good agreement with the lattice ones. The paper's conclusions underline the burnup and operation improvements brought by the increasing number of fuel elements inside of a CANDU bundle design.

Keywords: *CANDU, Advanced fuel bundle, Power fraction*

Introduction

The Romanian nuclear power sector is still dominated by the operation of two CANDU 6 units, two other units being under construction for a long time. Actually, Cernavoda Nuclear Power Plant with Unit 1 and 2 supplies about 20% of the total amount of electricity in the national energy system. Some financial schemes have been proposed over time in order to accomplish the building and commissioning of the CANDU Units 3 and 4, but none has succeeded. In this context, is clear that Romanian Nuclear short and medium term Strategy should take into account for the use of alternative fuel cycle in existing CANDU reactors. Moreover, the lack of strategic investors in deployment steps of the new units started to be built emphasizes once again the role of alternative fuel cycles as better cost-effective solutions to enhance both Uranium utilization and nuclear safety.

To cope with this situation, Romanian nuclear energy scientific community need to step its efforts in finding advanced CANDU fuels and fuel bundle configurations to meet the actual progress requests in nuclear energy field.

Advanced fuel designs for existing and future CANDU reactors have been proposed and studied over time by the Nuclear Fuel Performance Group (NFPG) in the Reactor Physics, Nuclear Fuel Performance and Nuclear Safety Department of RATEN ICN Pitesti. Recently, a new CANDU fuel bundle design with Increased Number of Elements (INE), whose design layout is inspired from [1], has been proposed for study. The fuel is Natural Uranium (NU) and entire bundle zircaloy assembly plus fuel will be referred as INE in the following.

The paper goal is to investigate burnup performances of INE fuel design for CANDU reactor irradiation conditions, comparatively to those of CANDU standard fuel design.

Methodology Outlines

Twin calculations have been performed for the two nuclear fuel designs: CANDU standard fuel (NU) in a standard 37-rods bundle (referred as STD) and in an advanced INE bundle with more than 37 rods. Fuel composition on the bundle rings (R1, R2, R3 and R4) is given in Table 1; Fig.1 presents a frontal view of the two bundle designs.

Table 1. The Fuel Bundle Composition

Config. #	**Fuel acronym**	**Fuel**	**Ring Fuel Mass** (kg)	**Uranium Ring Mass** (kg)	**Oxygen Ring Mass** (kg)	**Total mass per bundle U / O / UO_2** (kg)
1	STD	Uranium Dioxide (UO_2)	0.6 3.6 7.2 10.8	0.5 3.1 6. 9.4	0.1 0.4 0.8 1.3	19.5 / 2.6 / 22.1
2	INE	Uranium Dioxide (UO_2)	1.6 4.0 6.5 8.8	1.42 3.6 5.7 7.8	0.2 0.5 0.7 1.1	18. 5 / 2.5 / 20.9

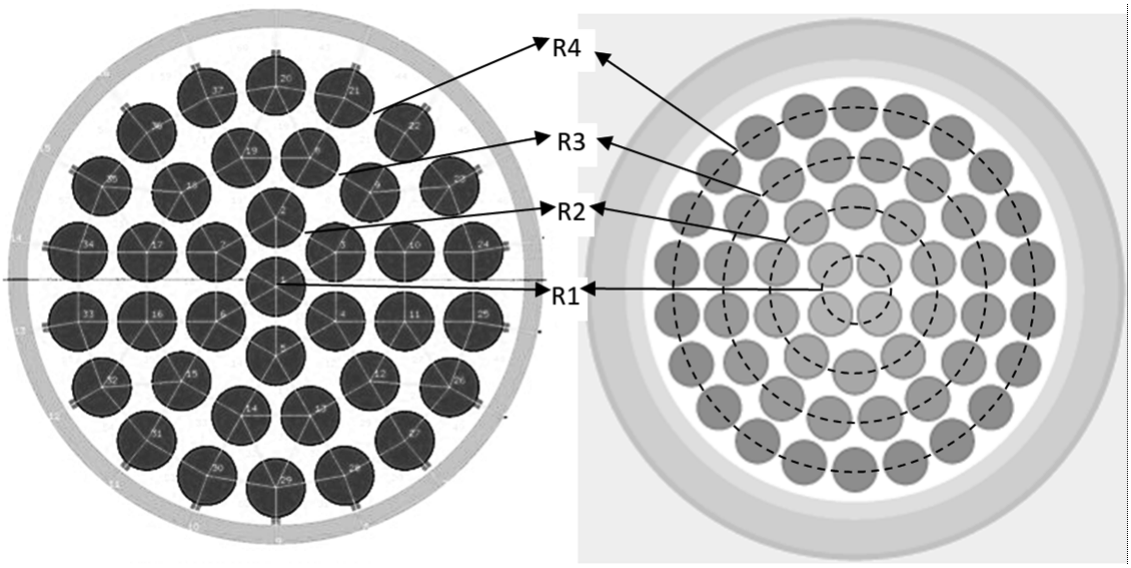


Fig. 1. STD (left) and advanced INE (right) bundles

The INE bundle design is similar to that of the 37-rods one, both having four rings of elements. The main difference consists in the presence of an increased number of elements on all fuel rings in order to gain a larger heat transfer surface allowing thus, for thermal hydraulic improvements.

To perform burnup calculations, the lattice modelling was firstly carried out. The basic unit of the CANDU reactor is the lattice cell containing the fuel bundle and the associated coolant, the pressure and calandria tubes, surrounded by a corresponding volume of moderator. The lattice properties depend on the physical dimensions and composition of its materials. Once the burning is started, the relative amounts of uranium and plutonium isotopes will change with respect to the irradiation and, as a result, nuclear properties will change. Neutronic properties of interest are caught into macroscopic effective cross sections.

In order to generate macroscopic cross sections' tables, lattice burnup calculations have been performed with the WIMS-D5B code [2] and the associated IAEA nuclear data library, [3]. Then, with these data and using a standard CANDU 6 core model [4, 5] adapted to the DIREN input [6-8], time average calculations have been carried out to complete the picture regarding the INE fuel design performances. Core average discharge burnups, maximum channel and bundle power along with ZCU reference radial power distribution will be presented and discussed.

Lattice calculations results

The infinite multiplication constants evolution versus irradiation for the considered fuel bundles is presented in Fig. 2, while Table 2 reveals the associated power peaking factors.

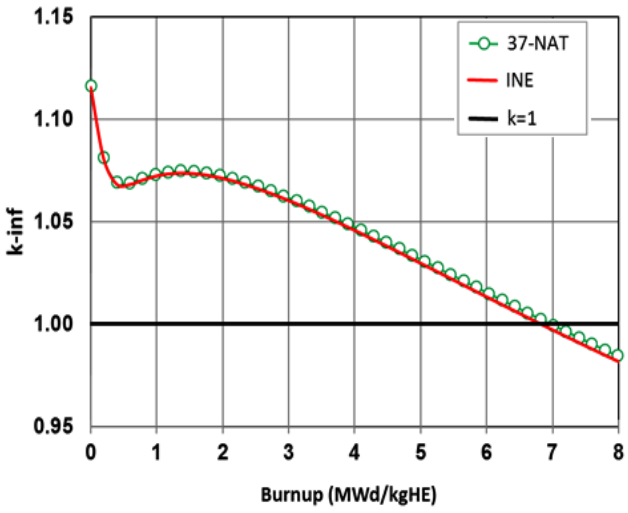


Fig. 2. Evolution of infinite multiplication constants with fuel irradiation

Table 2. Power Peaking Factors

STD Bundle Design	**R1**	**R2**	**R3**	**R4**	**R4-R1**
Fresh Fuel	0.777	0.813	0.912	1.134	0.357
Mid Burnup (3.7 MWd/kgU)	0.779	0.815	0.909	1.135	0.356
Exit Burnup (7.0 MWd/kgU)	0.799	0.831	0.915	1.124	0.325

INE Bundle Design	**R1**	**R2**	**R3**	**R4**	**R4-R1**
Fresh Fuel	0.797	0.844	0.944	1.149	0.352
Mid Burnup (3.7 MWd/kgU)	0.800	0.845	0.939	1.151	0.351
Exit Burnup (7.0 MWd/kgU)	0.818	0.859	0.940	1.141	0.323

The exit burnup values for both fuel designs are very close each other and close to 7.0 MWd/kgU. A fine interpolation between values shows that in spite the fact that INE fuel design contains 1 kgU less than STD design (that means about 5 % less Uranium), the INE exit burnup is only 1.8% less than that of STD design. This proves a more efficient burnup per unit mass of the nuclear fuel.

Power Peaking Factor (PPF) represents the relative linear power on a fuel ring, i.e. the ratio between average linear power on that ring and the average linear power on the bundle. In order to have a good power flattening in the fuel bundle it is preferable to have PPF values close to unit or difference between the innermost and the outermost fuel rings PPF values as small as possible. In the last column of Table 2, the differences between R4 and R1 PPF values are calculated. Slightly lower values were found out for INE design, comparing to those of STD, this denoting a slightly better power flattening.

Table 3 presents the power fractions (in percent) generated on bundle rings by the WIMS program, while in Table 4 the element power fractions (EPF) are shown. The EPF on a ring is calculated by dividing the power fraction on that ring to the number of elements in the ring.

Table 3. Power fractions on bundle rings (%)

STD	**R1**	**R2**	**R3**	**R4**
Fresh Fuel	2.1	13.2	29.6	55.2
Mid Burnup (3.7 MWd/kgU)	2.1	13.2	29.5	55.2
Exit Burnup (7.0 MWd/kgU)	2.2	13.5	29.7	54.6

INE	**R1**	**R2**	**R3**	**R4**
Fresh Fuel	6.1	16.2	29.1	48.6
Mid Burnup (3.7 MWd/kgU)	6.2	16.3	28.9	48.7
Exit Burnup (7.0 MWd/kgU)	6.3	16.5	28.9	48.3

Table 4. Element Power Fractions (%)

STD	**R1**	**R2**	**R3**	**R4**
Fresh Fuel	2.1	2.2	2.5	3.1
Mid Burnup (3.7 MWd/kgU)	2.1	2.2	2.5	3.1
Exit Burnup (7.0 MWd/kgU)	2.2	2.3	2.5	3.0

INE	**R1**	**R2**	**R3**	**R4**
Fresh Fuel	1.5	1.6	1.8	2.2
Mid Burnup (3.7 MWd/kgU)	1.5	1.6	1.8	2.2
Exit Burnup (7.0 MWd/kgU)	1.6	1.7	1.8	2.2

A comparison between the fuel bundles element power fractions is shown in Fig. 3. It can be easily noticed that the advanced INE fuel bundle design presents lower EPF values than those of the standard 37-rod fuel bundle design, denoting a better power flattening and a reduced element thermal stress in normal operation conditions.

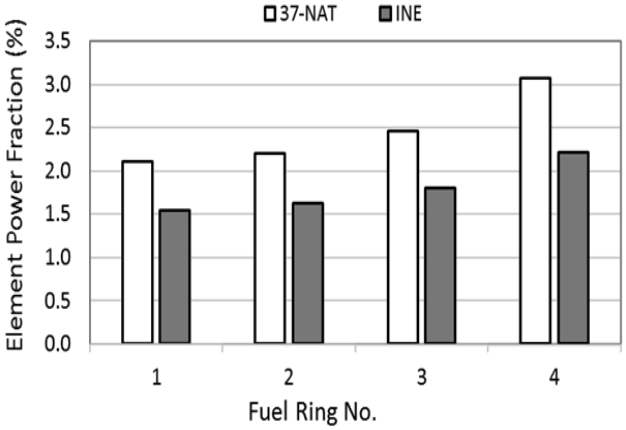


Fig. 3. Element power fractions

Core calculation results

Time average core calculations were performed for both fuel bundle designs in order to find out the discharge burnups on burnup regions, maximum channel and bundle power along with Zone Control Units (ZCU) reference radial power distribution. Table 5 presents the core relevant parameters for these core calculations, ADB denoting Average Discharge Burnup.

Table 5. Time-average core calculations results

Parameter	**STD**	**INE**
ZCU Powers (%)	16.6 13.0 12.9 14.8 13.0 12.9 16.6	16.6 12.9 12.9 14.9 12.9 12.9 16.6
ADB on Burnup regions (MWd/kgU)	*1 2 3 4* 6.4 7.5 6.6 5.9	*1 2 3 4* 6.0 7.1 6.3 5.6
Core ADB (MWd/kgU)	6.88	6.50
Max. Channel Power & Channel Location	6480 kW P8	6460 kW P8
Uranium mass per bundle (kg)	19.5	18.5
Max. Bundle Power & Bundle Location	786.6 kW P6- 6	786.2 kW P6- 6
k-effective	1.000074	0.99995
Core Reactivity (mk)	0.074	- 0.05
Refuelling Scheme	8-bundle shift	8-bundle shift

Core calculations results are similar for the considered fuel bundle designs, no notable differences being registered in terms of operation performance. The average discharge burnup value of INE fuel bundle design is 5% smaller than that of STD fuel bundle design, according to the Uranium mass.

From the point of view of fuel performance evaluation, but also for safety reasons it is important to calculate the Maximum Outer Element Linear Power (MOELP). A simple MOELP calculation can be done by multiplying the maximum bundle power by the outermost ring power fraction and then dividing it by the number of elements and bundle length.

For the standard 37-rod bundle design, we calculated a MOELP value of 48.5 kW/m (=786.6*0.55/18/0.495); for the INE fuel bundle design a comfortably lower value of 35.2 kW/m (=786.2*0.487/22/0.495) was obtained. Thus, through the time-average core calculations we found out that the advanced INE bundle design allows for about 28% reduction in thermal stress undergone by the outer ring elements in normal operation conditions. On the other side, it should be mentioned that inside of time-average approximation there are no refuelling operations explicitly taken into account, but only refuelling strategy. As a result, we consider our outer element linear powers values good enough for a prospective evaluation. A more precise MOELP calculation can be done through the simulation of refuelling operations. This is a planned task of our group in the near future.

Conclusions

The advanced INE fuel bundle with natural Uranium and more than 37 fuel rods offers promising result regarding the behaviour in normal operation conditions of a CANDU type power reactor.

Core calculations results obtained through the time-average approximation are in good agreement to the lattice ones.

Advanced core-follow simulations of refuelling operations are still needed in order to obtain more accurate values for parameters of interest regarding the fuel burnup performance and nuclear safety.

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