ADVANCED CANDU NUCLEAR FUEL ELEMENTS ANALYSIS

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Abstract
This paper assesses the fuel performance aspects of recently developed CANDU nuclear fuel bundles. In this respect, the new fuel bundle geometries with 37 elements C37M (CANDU37Modified) and with 43 elements CN43 (CANDUNew43), were taken into account. The fuel bundles behavior in pile was compared to that of the CANDU standard fuel bundle. All considered bundles contain natural uranium dioxide pellets (0.72% enrichment in U^{235}). The results of lattice calculations indicate that a lower thermal stress can be achieved using advanced design geometries. The linear outer element powers and power boosts along with thermo-mechanical parameters were also examined. The paper's conclusions underline the overall improvement brought by the advanced CANDU bundle geometry designs.

Keywords: *Fuel performance, new CANDU bundle geometry, Natural uranium dioxide pellets*

Introduction

With increased interest in CANDU technology in Romania's nuclear sector due to the advancements made in the building and commissioning agreement of Units 3 and 4 on Cernavoda NPP site between Romania and the United States of America and taking into account the requirement for stable and reliable electricity in the context of technological development, economic and population growth, and especially in the context of the SARS-CoV -2 pandemic, it is imperative that Romanian nuclear short and medium term strategy should consider the use of alternative fuel cycle and advanced fuel designs to cope to the up mentioned challenges.

In this regard, the Nuclear Fuel Performances Evaluation Department has conducted studies focused on the development of advanced nuclear fuel concepts suitable for the implementation in CANDU nuclear reactors.

Moreover, according to [1], electricity produced from nuclear long-term operation (LTO) by lifetime extension is not only stable but also highly competitive and remains among the lowest cost options for low-carbon generation. Nuclear option is a dispatchable low-carbon technology with the lowest expected costs in the near future [2].

The goal of the paper is to investigate some safety aspects along with the thermo-mechanical behaviour revealed by the use of two advanced CANDU bundle designs fed with Natural Uranium (NU) fuel, comparatively to the use of the CANDU standard 37-elements bundle design.

Fuel bundle design features

The considered bundle designs are illustrated in Fig.1 and described in Table 1. The nuclear fuel is natural uranium in form of uranium dioxide pellets, having a theoretical density of 10.7 g/cm^3.

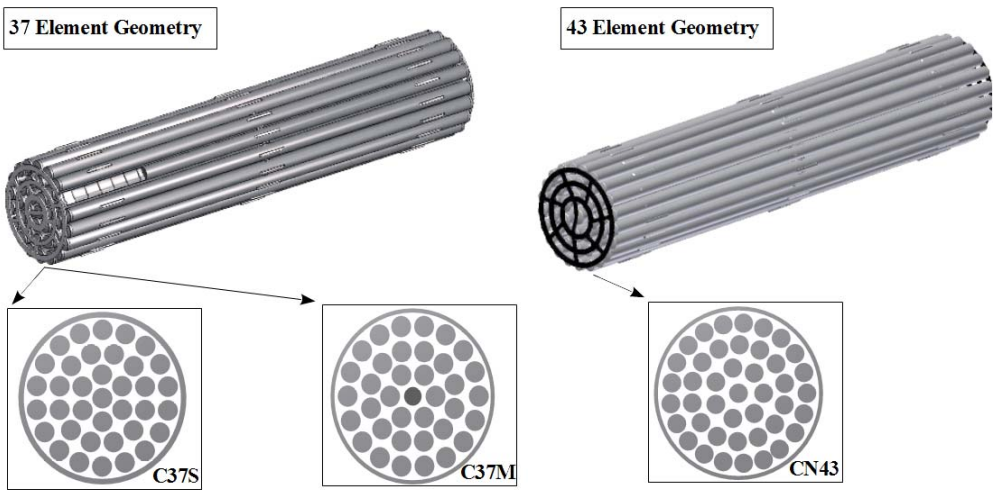


Fig. 1. The 37 (left) and 43 (right) CANDU fuel bundle geometry [3, 4]

Particularities of the fuel bundle designs can be resumed as follow: the first one is the 37-rods standard fuel bundle design which is nowadays used in actual CANDU power reactors, while the second one is the modified 37-rods fuel bundle design with the particularity of having a slightly reduced central pin.

The third bundle design is the 43-rods and represents the next evolutionary step for the *SEU-43* bundle design developed in ICN-Pitesti by means of diameter element reduction. Instead of having 2 types of fuel elements (thin elements - 11.5 mm and thick elements - 13.5 mm in diameter, respectively) like in the case of SEU-43 fuel bundle, the newly developed bundle (referred in paper as CN43) has 43 identical elements (12 mm in diameter), this feature allowing to reduce the fabrication costs. Also, the increased number of elements of smaller thickness is expected to reduce the element linear powers.

The geometrical characteristics of the mentioned fuel bundles are depicted in the table below. R1 to R3 denote the fuel rod rings, starting from the centre of the bundle (CE is a central element).

Table 1. The fuel bundle geometry characteristics [3, 4]

Fuel design	**C37**	**C37M**	**CN43**
Element distribution on rings	CE: 1 R1: 6 R2: 12 R3: 18	CE: 1 R1: 6 R2: 12 R3: 18	CE: 1 R1: 7 R2: 14 R3: 21
Fuel		UO_2 natural	
Clad material	Zy-4		
Clad outer diameter (mm)	13.1	CE: 11.5 R1-3: 13.1	12
Pellet outer diameter (mm)	12.2	CE: 10.7 R1-3: 12.2	11.2
Pellet number per element	29 +2 end pellets	CE: 34 +2 end pellets R1-3: 29 +2 end pellets	32 +2 end pellets
UO_2 mass (kg)	22.1	21.9	21.3
Total Zy-4 mass (kg)	2.14	2.13	2.23

* CE - Central fuel element; R1 - Inner ring of fuel elements; R2 - Intermediary ring of fuel elements, R3 - Outer ring of fuel elements

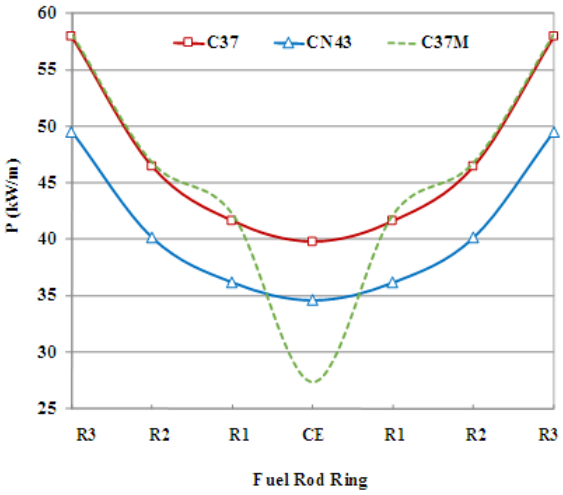


Fig. 2. The radial power distribution inside every fuel bundle project considered

Methodology outlines

Firstly, the lattice calculations were performed using the WIMS computer code [5] with the associated IAEA library [6], in order to obtain neutronic properties with respect to the burnup. The next step consists in performing Time-Average (TA) calculations to generate the reference power distribution and discharge burnups over the reactor core regions. CANDU reactors are refuelled on power and to take into account for the fuel burnup heterogeneity inside the reactor core at equilibrium state, a special Time Average (TA) approximation was developed [7]. Full core modelling was performed using the DIREN program [8].

Core calculations results and discussions

Lattice calculations allow for radial power distribution revealing inside every bundle. A design bundle power limit of 935 kW [9] was considered for every fuel bundle project in order to derive the corresponding ring linear powers. These are comparatively presented in Fig. 2.

More confident values for the element linear powers are expected from CFS () calculations where the maximum bundle powers supplied in real conditions simulation will be used.

The CFS maximum bundle powers along with ring power shares obtained in the lattice calculations allow finding the Maximum Outer Element Linear Power (MOELP) for every fuel bundle design. MOELP along with Maximum Outer Element Linear Power Boost (MOELPB) are often referred as *irradiation histories*. MOELPB originates in bundles` moving along a fuel channel during refuelling. Thus, a fuel bundle may endure different power levels, this resulting in linear power boosts. It should be noted that, in spite the fact that an outermost fuel element may cope well with a MOELP of 60 kW/m (for the 37-elements fuel bundle with natural uranium, for example) along its residence in the reactor core, it may only endure a MOELPB significantly lower, starting from 35 kW/m at loading into the core, and decreasing drastically by burnup to about 15 kW/m at the exit burnup [9]. Therefore, evaluating MOELP and MOELPB with respect to irradiation is a mandatory task for both safety reasons and fuel performance evaluation.

In Figs. 3 to 5, the irradiation histories are shown with respect to the fuel burnup for every of the four bundle designs. The fuel failure curves for MOELP and MOELPB correspond to the natural uranium dioxide fuel.

The linear power envelope, depicted in Fig. 6, directly derives from the irradiation histories and it consisting in the maximum OELP values recorded at every burnup, from zero to the exit (discharge) value.

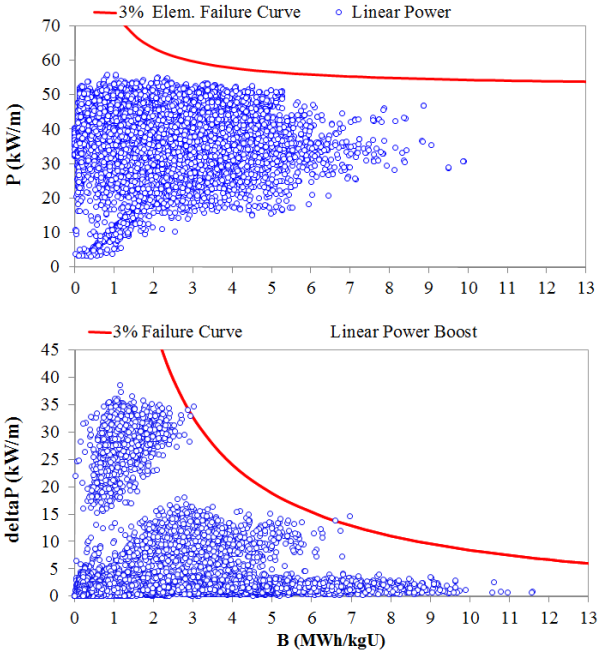


Fig. 3. C37 MOELP and MOELP evolution by burnup

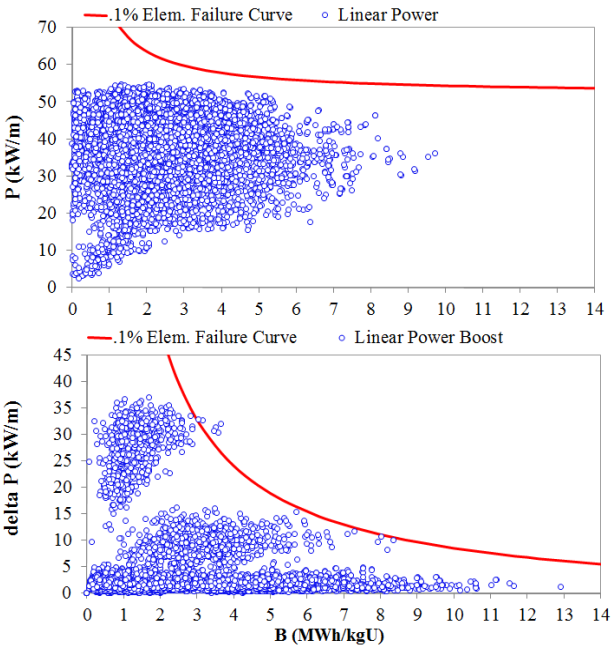


Fig. 4. C37M MOELP and MOELP evolution by burnup

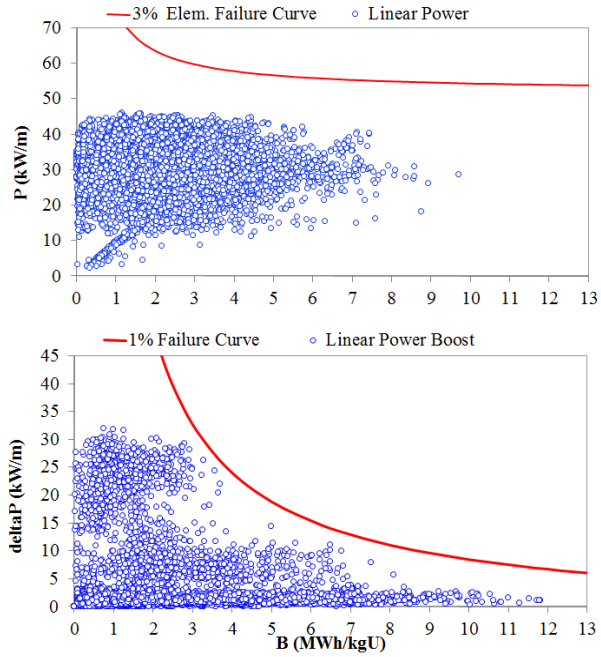


Fig. 5. CN43 MOELP and MOELP evolution by burnup

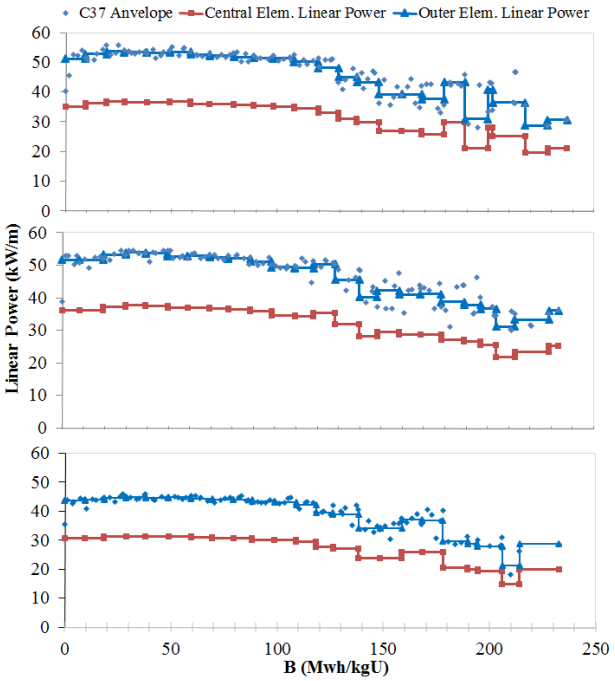


Fig. 6. Linear power envelope for C37, C37M and CN43

Thermo-mechanical assessment

To complete the analysis, the main thermo-mechanical parameters were estimated using the ROFEM computer program [10, 11] and represented below, as follow: pellet central temperature, fission gas release volume, fission gas conductance and heath transfer in radial gap, internal pressure and ridge height deformation.

With the largest uranium dioxide mass and identical diameters for all 37 elements (see Table 1), the C37 fuel bundle naturally supplied the highest linear power for outer and central elements (see Fig. 6). By increasing the number of fuel elements, the mass of uranium dioxide per element of the CN43 bundle design considerably reduced and the linear power curves drop accordingly. Therefore, the fuel operation behaviour becomes safer, see MOELP evolution.

As a direct consequence of having the largest linear power values (see Fig. 6), the C37 and C37M fuel bundles also presents the highest operation temperatures in the centre pellet region compared to those of the CN43 fuel design. As depicted in Fig. 7, the central pellet temperature evolution follows rigorously the linear power shape. Looking in comparison (Figs. 7 and 8), at temperatures over 1500 °C the fission gas release is accelerated for the C37 and C37M bundle designs, while for the CN43 bundle design the amount of fission gas released is very small.

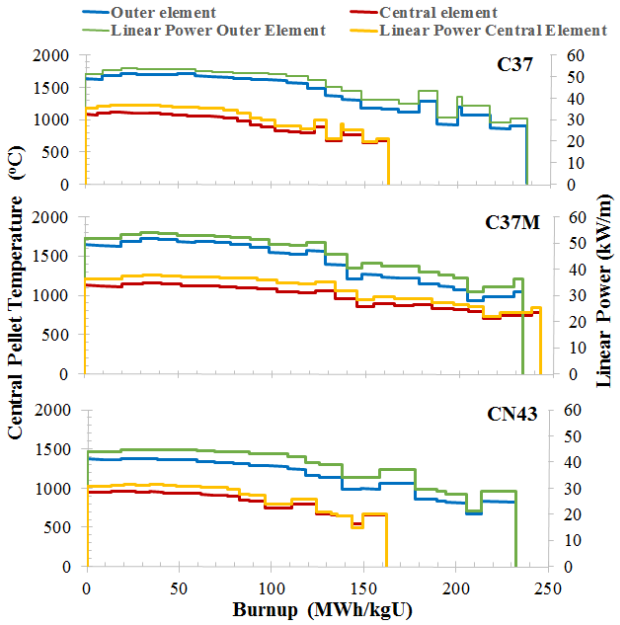


Fig. 7. Correlation between temperature in pellet central region and linear power

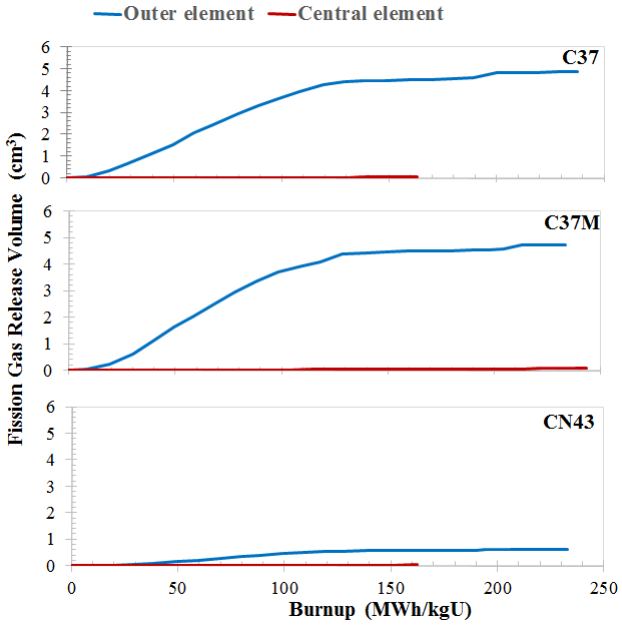


Fig. 8. Evolution of fission gas volume released inside the free volume of the element

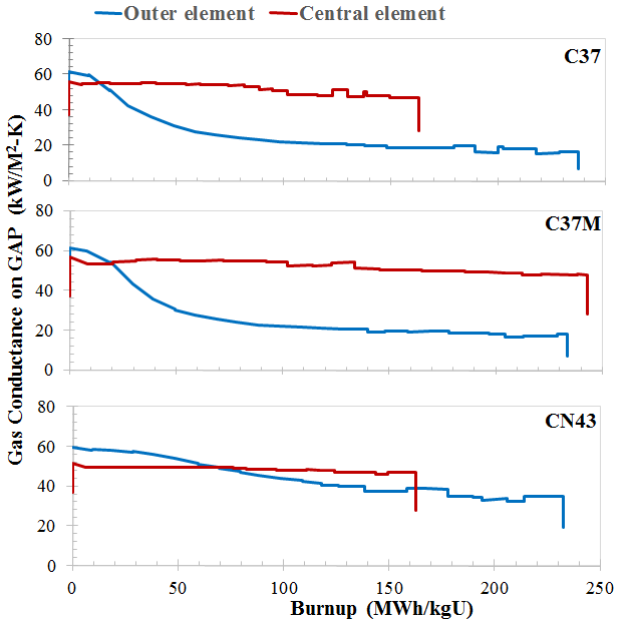


Fig. 9. Evolution of gas conductance in radial gap

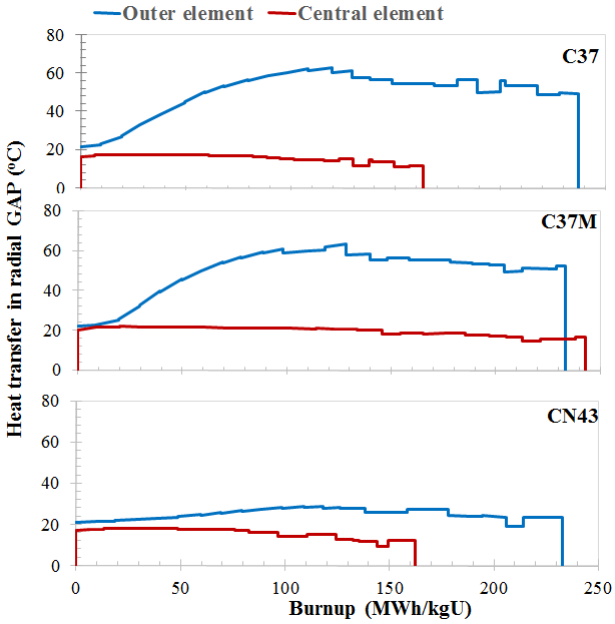


Fig. 10. Evolution of heath transfer in radial gap

A lower gas conductance coefficient alters the heath transfer between pellet surface and sheath inner surface and promotes an increased thermal stress, and vice versa, as depicted in Figs. 9 and 10.

Another consequence of the C37 and C37M fuel bundles operation at high OELP is the release of significantly larger amounts of fission gases comparatively with the CN43 advanced fuel bundle design. Consequently, this release is credited to the increasing of internal pressure inside of the clad. In Figs 8 and 11 the fission gas release volume and pressure were represented.

As far, the volume released by the 37 elements fuel bundle (standard and modified) designs are larger by almost three decades than that corresponding to the CN43 fuel bundle design.

Non-uniform temperature across the radius of the pellet, as well as axial compression and variations in initial density, promotes microstructural changes and may lead to the so called *hourglassing* phenomenon [12], when diametric fuel expansion at the pellet`s end is larger than the mid-plain one. The difference between pellet diameter at end plane and mid-plane is called *ridge height*, and is depicted in Fig. 12. The results obtained are within normal range.

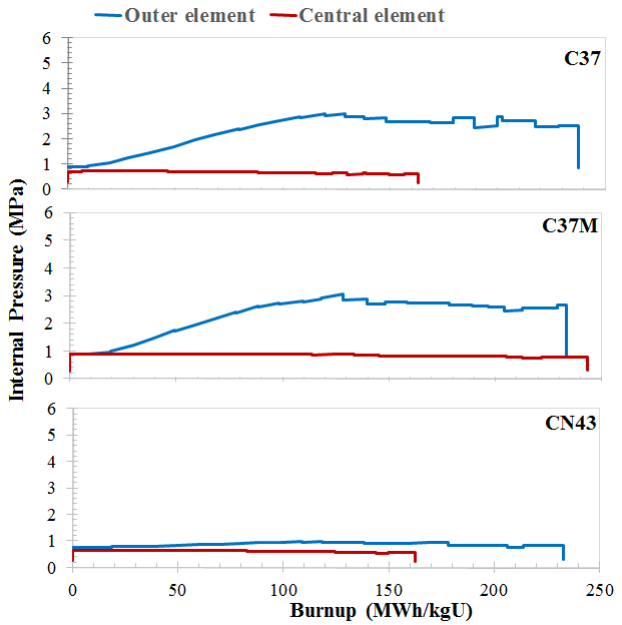


Fig. 11. Evolution of pressure accumulated in fuel element

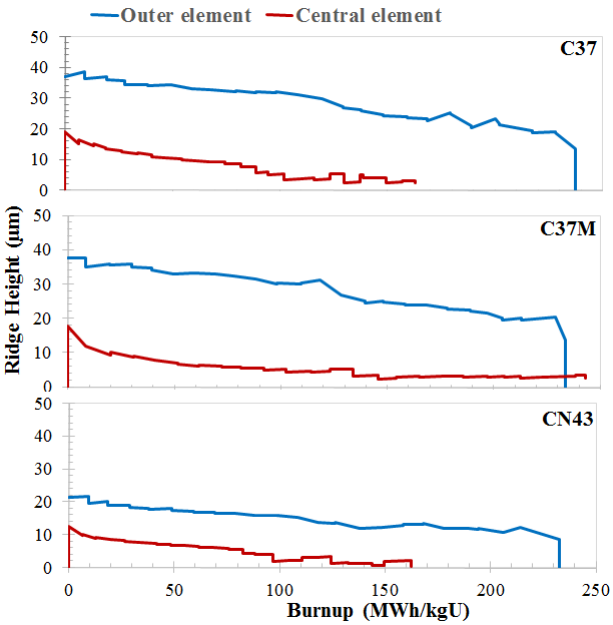


Fig. 12. Evolution of pellet ridge height

Conclusions

The advanced fuel bundle designs CN43 and C37M fed with natural uranium offer promising result regarding the behaviour in normal operation conditions of a CANDU power reactor.

By reducing the central element diameter, more cooling agent flows through the central region, thus the heat transfer in the C37M fuel bundle design is improved. Even though maximum central temperature marks a 3% increase comparatively with the C37 standard fuel bundle design, the curve evolution by burnup is smoothened.

The linear powers supplied by the CN43 fuel bundle improve the fuel thermo-mechanical performances. Thus, the fission gas release volume becomes three times lesser than in the case of C37 standard fuel bundle design.

The advantage of having an increased number of elements immediately results in improved safety performances for the CN43 fuel bundle, in normal operation conditions. Its outer element linear power and power boosts are considerably reduced this indicating safer irradiation behaviour. Moreover, the CN43 identical fuel elements may allow the manufacturing costs reduction.

The future work considers performing thermo-mechanical analyses associated to the use of the 52 and 61 elements advanced bundle designs in CANDU reactors.

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