NEUTRONIC ANALYSES OF A METALLIC U-ZR FUEL USING IN CANDU REACTORS

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Abstract

The paper evaluates neutronic lattice and core performances of a Uranium-Zirconium (U-Zr) cruciform, helically twisted, metallic fuel design. A composition of about 50-50% U-Zr inside the 37-rods fuel arrangement, suitable for loading in the CANDU standard fuel channel was considered. The specific design, which includes a central zirconium (Zr) or Burnable Absorber (BA) filled displacer, enables for reactivity control while significantly reducing the Coolant Void Reactivity (CVR). The equivalent initial fissile and BA contents were calculated to match the reactivity evolution during burnup of the CANDU standard fuel, while preserving the actual fuel cycle length. The influence on core integral parameters of interest, such as Average Discharge Burnup (ADB), axial power profile, and channel power distributions, is also presented and discussed.

Keywords: *Accident Tolerant Fuel (ATF), CANDU, burnup, Lightbridge Fuel, CVR*

Introduction

Following the Fukushima accident, the international nuclear energy community started to promote new fuel concepts, commonly referred to as Accident Tolerant Fuels (ATF), able to cope for a longer time period to accident conditions. The U-Zr based fuel is a promising solution for ATF concepts due to its improved physical properties such as: high thermal conductivity allowing operation at lower temperatures than those of the uranium dioxide (UO_2) standard fuel, and a very robust mechanical design as a result of absence of the gap and a specific metallurgically bonded fabrication technology, [1-3].

At the international level, the Lightbridge™ Company is focused on developing U-Zr fuels for both Light Water Reactors (LWR) and Pressurized Water Reactors (PHWR). Recent results coming from an international RATEN ICN conducted research contract have been released, revealing that the Lightbridge Fuel™[1] (LBF) design for PHWR has a good neutronic behavior, [1]. The goal of this paper is to contribute to the LBF preliminary neutronic analysis using an alternative methodology based on transport and diffusion calculations. In this respect, the study was carried out using WIMSD5B-NEA version [4] and 3D finite differences DIREN [5] programs.

Methodology Outlines

The basic characteristics of the LBF design for PHWR are underlined in [1], where detailed geometry MCNP models [6] have been developed and used to evaluate at the CANDU lattice level neutronic properties, like discharge burnup and equivalent enrichment to achieve the CANDU standard exit burnup. The actual Natural Uranium (NU) CANDU average exit or discharge burnup (ADB) is about 7.0 MWd/kgU, depending on the country and PHWR reactor model. Romania reported an operational ADB of 167-171 MWh/kgU (6.95-7.13 MWd/kgU) for Cernavoda Unit 1 and 2, respectively [7]. Aside from safety qualification procedures, introducing a new fuel design necessitates the preservation of at least the actual CANDU ADB.

The paper's first goal was to obtain the initial equivalent uranium enrichment that leads to appropriate neutronic lattice properties while preserving the real CANDU ADB provided by core time average (TA) calculations. Due to the fact that LBF fuel contains only about 50% uranium, as opposed to the standard uranium dioxide (UO_2) with more than 88% uranium content, it is necessary to use slightly enriched uranium (SEU) in order to maintain the fuel cycle length. Despite homogenization procedures within the elementary CANDU standard lattice cell shown in Figure 1, [8], the diffusion methodology used in core calculations takes into account for the CANDU core layout, the presence of reactivity devices through incremental cross-sections, the reflector surrounding the core, and reactor core boundary conditions through the extrapolation distance. The CANDU standard 37-rod fuel bundle layout is shown in Figure 2.

The cruciform LBF rod reproduced in Figure 3 [1] is one of the 37 rods in the WIMS model, as seen in Figure 4. Since only cylindrical geometry is allowed in the WIMS model, the real lateral area of the LBF rod was kept along with the fuel mass, resulting in a lower fuel density and a bit larger element radius, accordingly. LBF also employed the CANDU 37-rod fuel bundle layout.

[1] Lighbridge Fuel is a trademark of Lightbridge Corporation, Reston, Virginia, USA

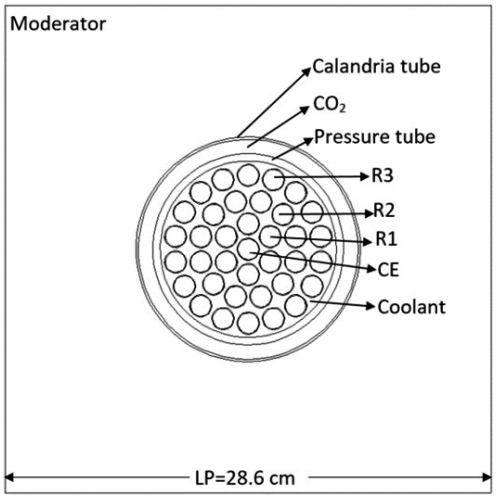


Fig. 1. CANDU lattice cell (at scale), [8]

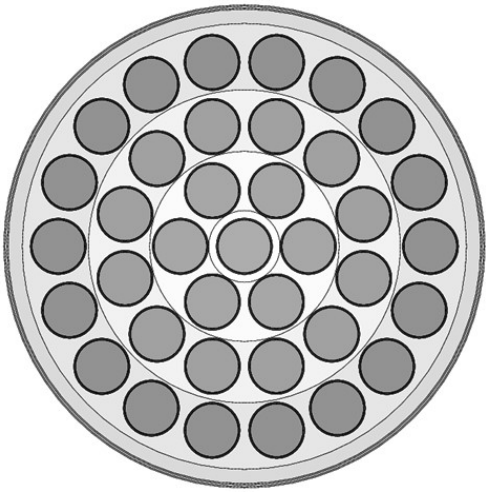


Fig. 2. CANDU 37-rod fuel bundle layout



Fig. 3. LBF element, [1]

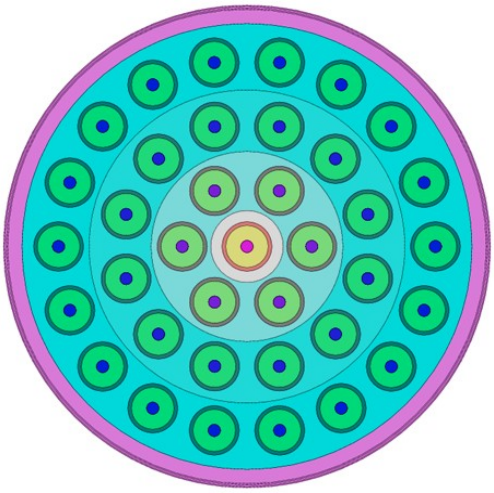


Fig. 4. CANDU LBF WIMS model

Three configurations corresponding to the 37-fuel rods CANDU standard and LBF designs are considered for lattice and core calculations, as in Table 1.

The cross sections table sets generated by the transport calculations with respect to the burnup were collapsed into 2-group energy values and introduced in a standard CANDU 6 core model [9, 10], which was adapted for the DIREN computer program. The time average approximation [11] was used to obtain integral core parameters of interest, such as average discharge burnup, channel and bundle power distributions, and effective multiplication constant. Four burnup regions and eight bundle-shift scheme were used, as shown in Figures 5 and 6. Small digits (1 to 4) signify the burnup regions, whereas larger ones (1 to 7) denote the light water Zone Control Unit (ZCU) power regions, with ZCU being the main system for a fine reactivity control in CANDU.

Table 1. Working Configurations and Fuel Characteristics

Acronym	**C37-NU**	**LBF no BA**	**LBF + BA**
Config.#	*1*	*2*	*3*
Fuel matrix	UO_2	U-Zr	U-Zr
Central displacer	-	Zr	Zr in CE,R1,R2 Zr+ ~ 20% Er in R3
Clad	Zircaloy-4	Zircaloy-4	Zircaloy-4
Fuel element geometry	cylindrical	cruciform	cruciform
Initial enrichment (%U235)	0.711	1.195*	~ 2*

* These values were found out after series of combined lattice and core TA calculations

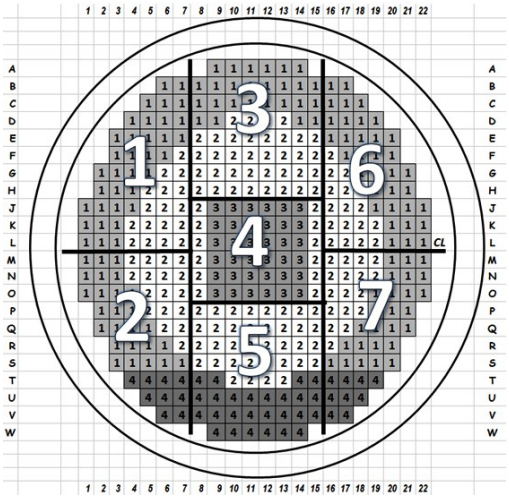


Fig. 5. Burnup regions (small digits) along with ZCU power regions (large digits), [12]

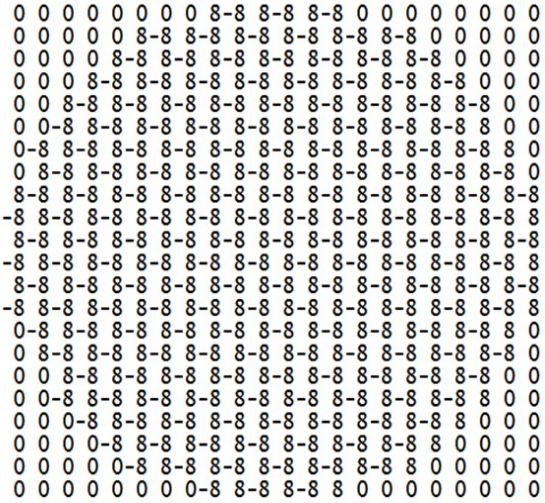


Fig. 6. Eight bundle shift scheme, [8]

The 3D finite differences DIREN program has been developed in RATEN ICN throughout the years and previous comparisons with RFSP-IST, [13], showed sufficiently close results in overall calculation options, particularly for the UO_2 matrix NU fuel design, [14].

A safety issue of the CANDU concept is represented by its positive Coolant Void Reactivity (CVR), which means that core reactivity increases in the event of loss of coolant accident. A simplified model of coolant voiding was applied at the lattice level by simply reducing the coolant density by 100 times.

Aside from infinite multiplication constant and reactivity evolutions, the CVR along with axial power profiles and reference time-average power shapes have been also represented comparatively for the standard CANDU and LBF designs. Comments are made in the Results section.

Lattice calculation results

The infinite multiplication constant and reactivity evolutions versus irradiation for the various considered configurations are illustrated in Figures 7 and 8.

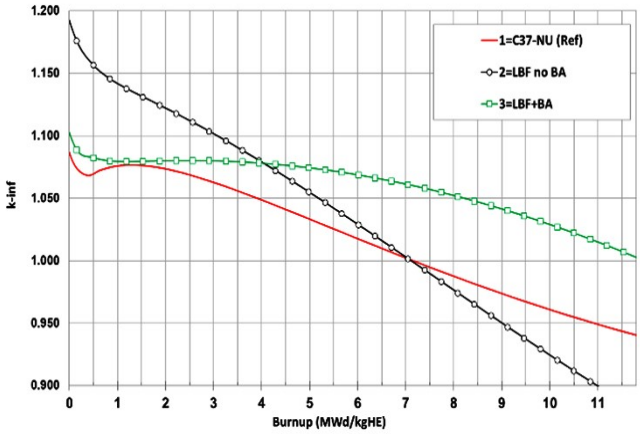


Fig. 7. k-inf versus burnup

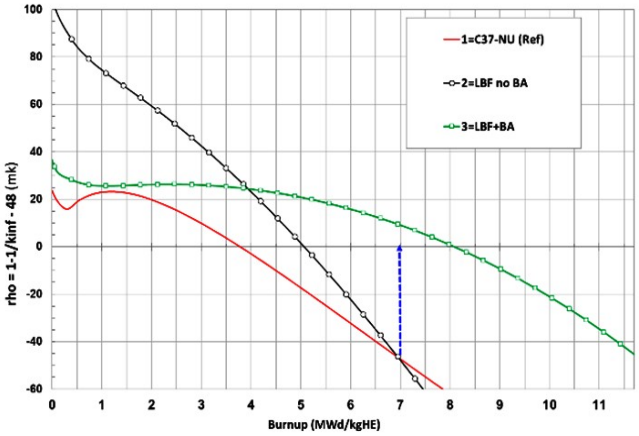


Fig. 8. Reactivity versus burnup

For Configs. #1 and #2, the instantaneous critical burnup value (i.e. the burnup corresponding to the k-inf=1) is about 7.0 MWd/kgU, whereas LBF+BA provides a significantly larger value. However, according to Rouben, [11], a full core time-average calculation is required to obtain a more accurate ADB value.

The "LBF no BA" design presents a faster reactivity decreasing by burnup compared to the standard fuel design, this being suggested by a larger slope of the k-infinite curve. As a result, the refueling operations for this design are expected to be more frequently if the current 8-bundle shift scheme is maintained.

In order to get closer to the initial CANDU standard reactivity excess and to get the same slope of k-infinity curve, a parametric study was performed. The green curve represents the third configuration, "LBF+BA", which used a mix of ~ 2% SEU along with about 20% erbium in the outermost ring displacers to shape the CANDU standard k-inf slope and core ADB.

The coolant void reactivity (CVR) was calculated as in formula given below, and the corresponding values with respect to the burnup are shown in Figure 9.

$$CVR\ (mk) = (1/kinf_{void} - 1/kinf_{cooled}) * 1000$$

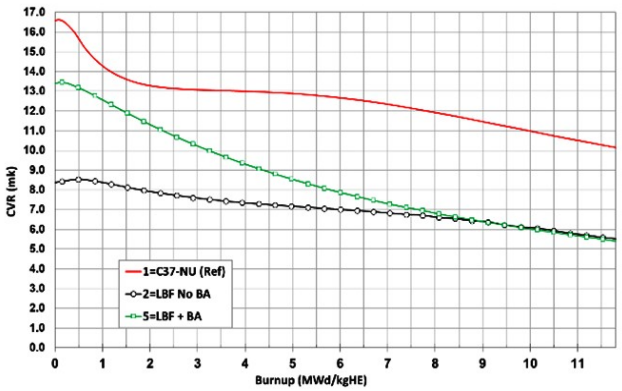


Fig. 9. CVR versus burnup

A general CVR diminishing by burnup is observed, especially for Configs. #1 and 3, while Config. #2 reveals an attenuated effect of burnup on the CVR. The results also show that CVR is drastically reduced, approximately by half, at glance, especially when the LBF design of Config. #2 is used (see black line with circles, in Figure 9). It is clear that the considered LBF designs contribute to the nuclear safety improvement of CANDU design.

Core calculations results

The time-average approximation yields an average value of discharge burnup (ADB) over the reactor core based on previously calculated lattice neutronic characteristics. To achieve a desired ADB, the burnup values on the four burnup regions shown in Figure 5 must be varied to obtain a critical core and a maximum value of about 6.5 MW. Taking the 7.0 MWd/kg as a reference value for ADB, the following results were obtained and presented in Table 2.

Table 2. Time-average results

Acronym	**C37-NU**	**LBF no BA**	**LBF+BA**
Config. #	1	2	3
Initial enrichment (%U235)	0.711	1.195	~ 2
Core reactivity (mk)	-0.1	-0.1	-0.1
Maximum channel power (kW)	6490	6460	6700
Maximum bundle power (kW)	788	790	765
ADB (MWd/kgU)	7.0	7.0	7.15
Refueling scheme (#bundle shift)	8	8	8
Form factor	0.84	0.84	0.81
Reactivity decrease (mk/FPD*)	-0.22	-1.7	-0.21

*FPD = Full Power Day

The obtained equivalent ^{235}U enrichment for LBF design with no BAin order to preserve the actual length of the standard CANDU fuel cycle is 1.195%, which is similar to the 1.138% provided by MCNP calculations in [1]. The relative difference is about 5%. Diffusion approximations used in the present work led to slightly greater enrichment, most likely due to the penalties for neutron leakage and reactivity devices, which are explicitly taken into account in the DIREN full core model. The third configuration (LBF+BA) is closer to the CANDU standard design because it preserves both the slope of k-inf with respect to the burnup while decreasing daily reactivity (about -0.2mk/FPD). Thus, it could be more suitable for refueling simulations, which were not performed in this work.

The present 3D diffusion-based simulations have also revealed considerable important differences in the fuel bundle consumption, which may significantly increase for the LBF reference design with no BA (Config. #2) due to a lower uranium content in the bundle compared to the CANDU standard one. In this respect, refueling calculations have to be performed using appropriate bundle shift schemes to validate these preliminary time-average results.

On the other hand, a way to simply reduce the fuel bundle consumption would be increasing the uranium content of the U-Zr alloy, rather of only enrichment. It is known that about half of the thermal energy in CANDU is produced by fissions in Pu-239, which is generated in situ from ^{238}U by nuclear reaction transmutations, such that more uranium implies more plutonium, and therefore more thermal energy available. However, this solution of increasing the U content is not sustainable because might affect key features of the Lightbridge fuel. One of them is that it is a delta phase uranium-zirconium alloy with low swelling upon irradiation, according to [15]. In contrast, U-Zr alloys with higher uranium content (such as the 90% uranium - 10% zirconium traditionally used in Sodium Fast Reactors) exhibit considerable swelling during irradiation that makes these high-uranium alloys unsuitable for use in monolithic metallic fuel rods, [15]. While there is some flexibility for adjusting the uranium content in Lightbridge Fuel, the acceptable range for keeping the alloy in the delta phase is rather small, at about 50 wt% uranium and 50 wt% zirconium [16]. As a result, increasing uranium content is limited to the threshold at which the delta phase of the U-Zr alloy changes.

Another way to improve the LBF economics is to consider using burnable absorbers (e.g., Erbium) in the central displacer along with a slightly increased enrichment (to ~ 2%), as in the case of Config. #3. The WIMS calculations reveal that the LBF k-inf slope would become similar to that of the standard CANDU fuel design. The initial lattice reactivity in k-inf spectrum and the core ADB are also closer to those of the CANDU standard design (~ 80 mk and ~ 7MWd/kgU, respectively). Moreover, the daily reactivity decrease is only -0.21 mk/FPD, which is quite similar to the reference one (-0.22 mk/FPD).

It is recognized that core refueling simulations are strongly needed to validate these preliminary calculations. Despite providing good results for NU and SEU fuels in different CANDU bundles with innovative geometries [12, 17-19], as well as LBF equivalent enrichment compared to Monte Carlo calculations, the DIREN input data for future LBF refueling simulations must be carefully built. Sensitivity studies on bundle consumption when the fuel matrix is changed while uranium amount is gradually reduced in the standard CANDU bundle are still necessary, and the results must be validated using stochastic evaluations or experimental data, if available.

The average axial power profile and core channel power shape for the three considered configurations are represented in Figures 10, 11, 12 and 13.

All the core power shapes are similar, while the axial ones differ by only several percents. It is appreciated that all fuel designs may perform well in a typical CANDU core, but each design has peculiar economics that must be further investigated in greater detail.

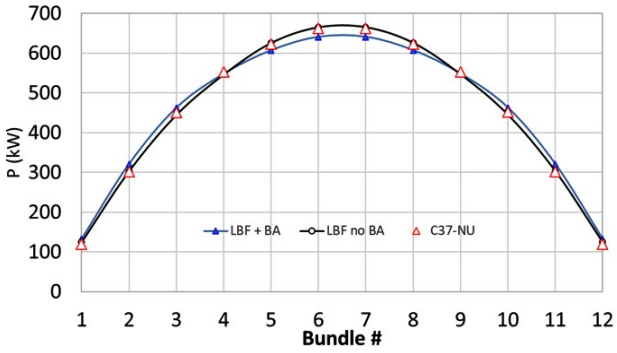


Fig. 10. Average axial power profile for C37 standard and LBF designs

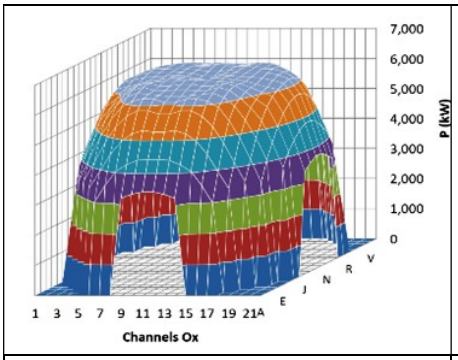


Fig. 11. Core channel power shape for C37-NU

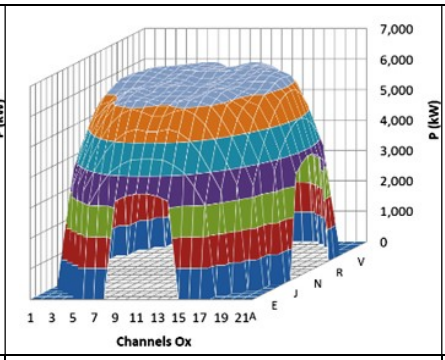


Fig. 12. Core channel power shape for LBF no BA

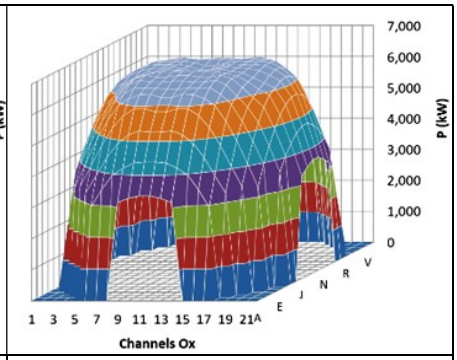


Fig. 13. Core channel power shape for LBF+BA

Conclusions

This preliminary study shows that the Lightbridge fuel designs under consideration offer obvious improvements in the nuclear safety of CANDU reactors by significantly reducing coolant void reactivity.

The obtained equivalent ^{235}U enrichment for the LBF reference design (no BA) in order to preserve the actual length of the standard CANDU fuel cycle is 1.195%, which is close to 1.138% obtained from previously performed Monte-Carlo calculations. The relative difference is about 5% and can be assigned to differences in the two modeling approaches, one being based on transport and diffusion approximations and the other employing stochastic methods.

In the present approach, reactivity penalties due to the reactivity devices and core leakage have been explicitly taken into account via incremental cross sections and an extrapolation length, while the Monte-Carlo approach simply considers a rough reactivity penalty of about -50 mk.

Increasing the uranium content of the U-Zr alloy could be an easy way to improve the economics of LB fuel, but a great attention must be paid to maintaining the delta phase of the alloy, in order to preserve the LB key safety features. Another way to increase the economics while approaching to the CANDU standard fuel behavior is the use SEU along with burnable absorbers.

Core refueling simulations are strongly needed in order to validate these preliminary calculations. Sensitivity studies on bundle consumption when uranium amount is gradually reduced in the standard CANDU bundle are still necessary, and the obtained results must be subject of validation against stochastic evaluations or experimental data, if available.

Acknowledgments
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