REACTOR PHYSICS ASPECTS ASSOCIATED TO THE CONVERSION OF A CANDU REACTOR CORE FUELLED WITH NATURAL URANIUM TO NUE FUEL

IOSIF PRODEA

Institute for Nuclear Research (RATEN ICN), Piteşti, Romania
e-mail: iosif.prodea@nuclear.ro

Abstract

The flexibility of CANDU reactor to accommodate advanced nuclear fuel designs has been proved along the years by many studies. A Natural Uranium Equivalent (NUE) fuel option is envisaged in this study to be used in a generic CANDU power reactor. The considered NUE nuclear fuel sort is a mixture of 21% Depleted Uranium (DU) and Recycled Uranium (RU) as balance. The using of DU and RU is environmental friendly because both are very abundant by-products coming from Light Water Reactors (LWR) enrichment and reprocessing programs. Moreover, LWR is nowadays the most widespread kind of nuclear power technology in the world and its by-product amounts continue to accumulate. The paper's idea is to gradually convert a Natural Uranium (NU) fuelled core at equilibrium state to NUE fuel. In this respect, the NU nuclear cross sections have been changed to those of NUE at the moment of refuelling start. The Reactor Physics aspects pursued during transition from NU to NUE fuel and presented as results consist in: refuelling frequency, fuel consumption, and average core burnup along with safety parameters like maximum channel and bundle powers. The paper's conclusions state that such a core conversion from NU to NUE fuel is possible to be achieved shaping the imposed NU power envelope and subsequently leading to slightly improvements in the fuel burnup.

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

Introduction

Romanian nuclear power energy sector is represented by the two 700 MWe output CANDU 6 units in operation at Cernavoda Nuclear Power Plant (NPP). The construction of other two CANDU units has suffered many delays, their commissioning schedule being nowadays, uncertain. Until now, Unit 1 and 2 generated about 20% of the total electricity amount in the national energy system. Different financial schemes proposed over the time, in order to accomplish the construction of Units 3 and 4, have unfortunately failed. On the other side, the flexibility of CANDU reactor to accommodate advanced nuclear fuel designs has been proved along the years by many studies, [1-3]. In the context of depletion of the national Uranium resources, Romania has to take into account for the use of alternative fuel cycles in actual CANDU units. An alternative fuel cycle option based on Natural Uranium Equivalent (NUE) using is seen as a better cost-effective solution, able to enhance both Uranium utilization and nuclear safety [4]. In this respect, a sort of NUE fuel based on 79% Recycled Uranium (RU) and 21% Depleted Uranium (DU) is considered in the present approach to be used in refuelling of a Natural Uranium (NU) CANDU core.

The goal of the paper is to investigate burnup performances and reactor physics aspects revealed by a gradually conversion process of a CANDU core fuelled with NU fuel, to a full NUE core.

Methodology Outlines

The paper's idea is to simulate fuel burnup on 10 Full Power Days (FPD) intervals in a CANDU NU fuelled core until the initial reactivity excess is exhausted, then to change the NU lattice cross sections to those of NUE fuel. Thus, for a few hundred FPD starting from the first refuelling day (usually the 130^{th} day), the reactor core is a mixture of NU and NUE fuels, then the NU bundles' number continues to decrease until they are completely replaced by the NUE ones, and a full NUE fuel core is obtained. The reactor core behaviour will be revealed through performing core burnup simulation over 710 FPD, a time interval considered to be sufficient for the reactor core to attain its equilibrium state.

The lattice modelling was firstly carried out in order to obtain neutronic properties. The basic unit of the CANDU reactor is the lattice cell containing the fuel bundle and associated coolant, pressure and calandria tubes, surrounded by a corresponding volume of moderator, as in Fig. 1. The lattice properties depend on the physical dimensions and material compositions. The nuclear fuel burning process changes the lattice neutronic properties and these modifications are captured in macroscopic effective cross section tables with respect to the burnup. Two sets of macroscopic effective cross sections are generated for NU and NUE fuels, on each of the 71 time steps which divide the 710 FPD irradiation interval considered.

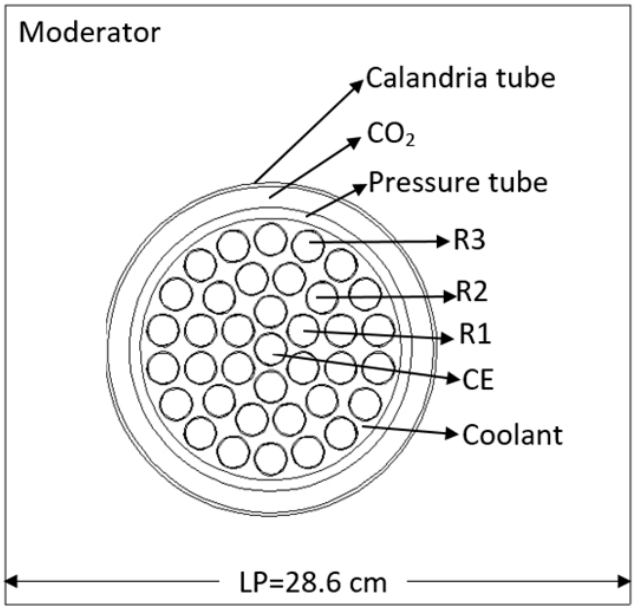


Fig.1. CANDU lattice cell (at scale)

In Fig. 1, where the CANDU lattice cell is represented at scale, CE, R1, R2, R3 denotes the central fuel element, followed by the element fuel rings (internal, intermediary, and external), while LP is the lattice pitch (28.6 cm). The NU and NUE fuel compositions are presented in Table 1.

Table 1. Isotopic NU and NUE Fuel Composition

Isotop	NU	NUE
U234 (%)	0	0.119
U235 (%)	0.635	0.681
U236 (%)	0	0.668
U238 (%)	87.520	86.68
O (%)	11.845	11.85

Lattice burnup calculations have been performed using the WIMS-D5B code [5] and associated IAEA nuclear data library [6]. Then, the cross section tables were introduced in a standard CANDU 6 core model [7, 8] adapted to the DIREN data input [9-11], and *time average* calculations have been carried out to obtain the reference burnup and power distributions over the reactor core. The reference NU channel and bundle power distributions were also imposed to be shaped by the NUE fuel using during the next steps of burnup advancing, when refuelling operations have been taken into account, explicitly.

Core average discharge burnups, maximum channel and bundle power along with maximum outer element linear powers and power boosts will be presented and discussed in the following.

Fig. 2 illustrates a frontal view of the CANDU standard 37-rods fuel bundle used as carrier for both sorts of nuclear fuels.

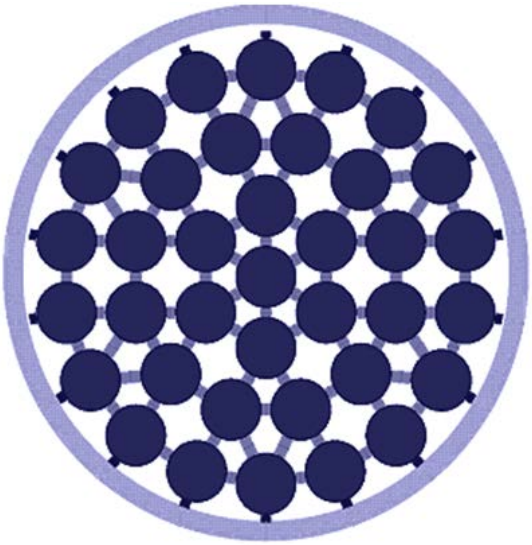


Fig.2. 37-rods fuel bundle

Lattice calculations results

The infinite multiplication constants evolution versus irradiation for the considered fuel sorts is presented in Fig. 3. The instantaneous critical burnup value (i.e. the burnup corresponding to the k-inf=1) is close to 7.0 MWd/kg for both fuel sorts.

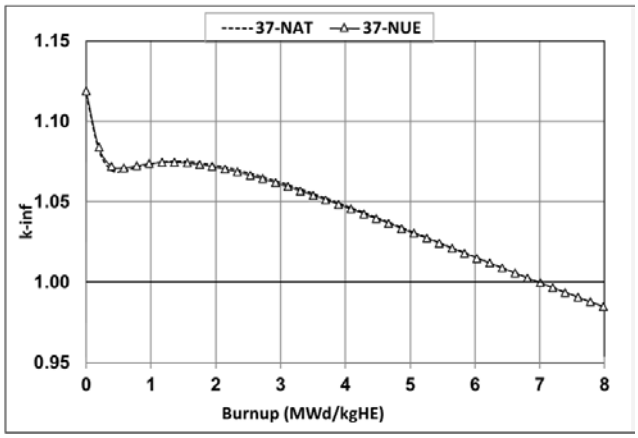


Fig.3. Evolution of infinite multiplication constant with fuel irradiation

Thus, the condition to have the same instantaneous critical burnup to achieve a natural Uranium equivalent fuel sort has been satisfied, as the lattice results show.

Core calculations results

The time average (TA) core calculations were performed separately, for both fuel designs (NU and NUE) in order to find out the core average discharge burnup (ADB), maximum channel and bundle power along with Zone Control Units (ZCU) reference radial power distributions. The core TA relevant parameters are given in Table 2.

TA calculations offer a picture of an equilibrium core fuelled by a single sort of fuel. Thus, deviations of a pure NUE fuelled core parameters from those of NU fuelled core can be emphasized. Table 2 presents a comparison of relevant TA parameters between NU and NUE fuel sorts.

Table 2. Time-average core results

Parameter	NU	NUE
ZCU Powers (%)	16.61 12.98 12.96 14.87 12.99 12.97 16.61	16.59 13.01 12.98 14.85 13.02 12.99 16.61
Core ADB (MWd/kgU)	7.06	7.12
Max. Chann. Power & Channel Location	6462 kW P8	6440 kW P8
Uranium mass per bundle (kg)	19.49	19.49
Max.Bundle Power & Bundle Location	787 kW P6- 6	788 kW P6- 6
Core Reactivity (mk)	0.016	0.053
Refuelling Scheme	8-bundle shift	8-bundle shift
Refuelling (dwell) time (FPD)	201	203

The results are similar for the considered fuel designs, no notable differences being visible in terms of operation performance. The average discharge burnup (ADB) of NUE fuel is about only 1% increased than that of NU fuel (7.12 vs. 7.06 MWd/kgHE), thus premises to have slightly improved burnup performances during refuelling being created. The TA safety parameters like maximum channel and bundle powers are situated in the expected range, important margins to the CANDU license limit values (7300 kW and 935 kW, [12]) being kept. Again, these results offer only a rough image of the cores' behaviour on average, as in the case when all refuelling operations are performed simultaneously, without taking into account for their day by day schedule. The main conclusion is that, supplying very close TA values to those of NU fuel, the using of considered NUE fuel option can shape the NU reference burnup and power distributions.

After performing refuelling burnup calculation for 710 FPD, more realistic values for safety parameters are expected to be obtained because the refuelling operations are explicitly taken into account in each 10 FPD interval. During refuelling operations significant increases of channel and bundle powers may occur due to decreasing the coolant velocity inside of refuelled channel and also, due to a larger fresh fuel reactivity excess. This increased thermal burden on fuel bundles along the fuel channel is caught by the DIREN core results and presented in Figs. 4 and 5. In this stage of analysis, the ″NU″ symbol means that the refuelling simulations are performed for a pure NU initially loaded and refuelled core, while the ″(NU+NUE)″ symbol is used to show that the core is initially loaded with NU fuel, and then it is refuelled with NUE bundles.

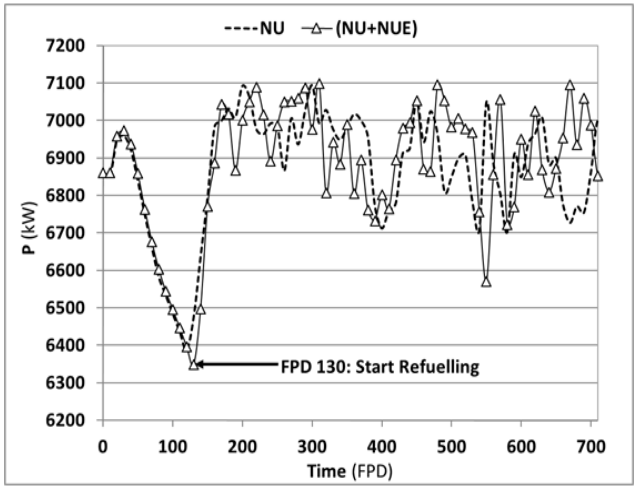


Fig.4. Maximum channel power evolution

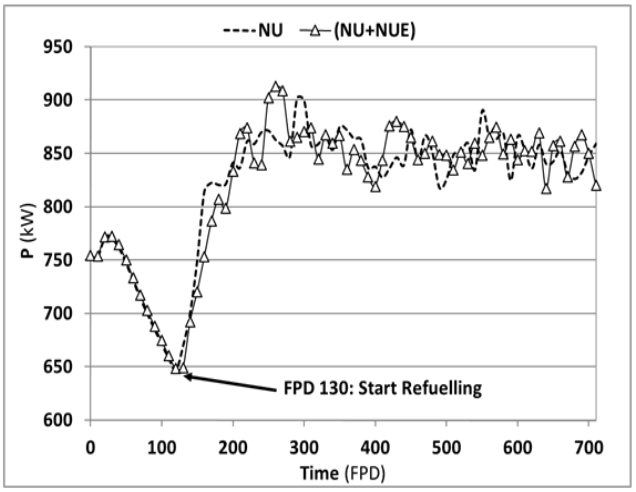


Fig.5. Maximum bundle power evolution

The shape of both maximum channel and bundle power values is strongly influenced by the moment of refuelling operations' start. After an easy increase due to Plutonium peak in the first 40-50 FPD, the maximum channel and bundle power values constantly decrease with the same slope for both fuels considered, until the refuelling start (130 FPD). Another increasing, more rapid than the previous one is shown starting with the 130th day, when NU fuel bundles become to be gradually replaced by NUE fuel bundles. The Maximum Channel Power (MCP) values reach the imposed value in the DIREN refuelling routines (7100 kW) several times, but this is not an issue as long as there are more than 200 kW up to the license limit [12].

The Maximum Bundle Power (MBP) values override for a while 900 kW during the (270-300 FPD) interval, this being the most challenging period of the core conversion process. After 300 FPD, the MBP values reach only 850 kW several times. In this stage of analysis, it can be roughly concluded that the core conversion process from NU to NUE fuel is possible to be achieved without dangerous MCP and MBP tilts.

On the other hand, 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) and the Maximum Linear Power Boost (MOELPB). The DIREN calculated bundle powers are converted in outer element linear power (OELP), knowing the number of elements and ring power shares from lattice calculations.

Thus, the OELP (in kW/m) is obtained multiplying the maximum bundle power MBP (in kW) by the outer ring share value and dividing by the bundle length and also, by the number of elements on the outer fuel ring (18, in the CANDU 37-rods bundle case). As the number of refueled bundles along with the initial loaded one override 15,000, the OELP and OELPB values generate distributions like those illustrated in Figs. 6-9.

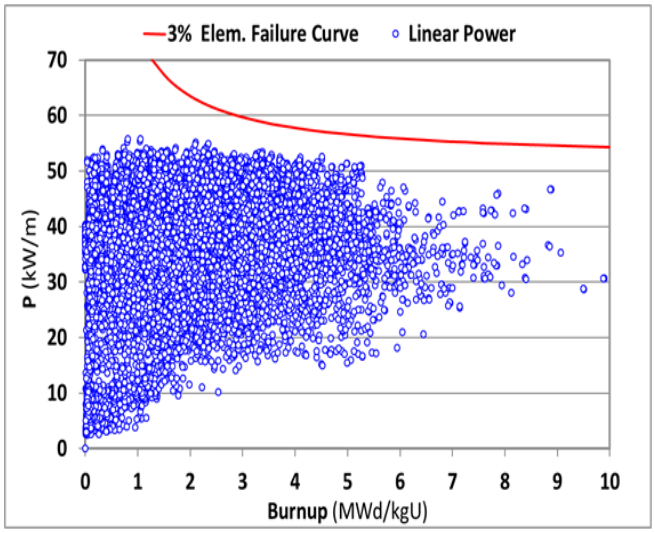


Fig.6. NU Linear Power

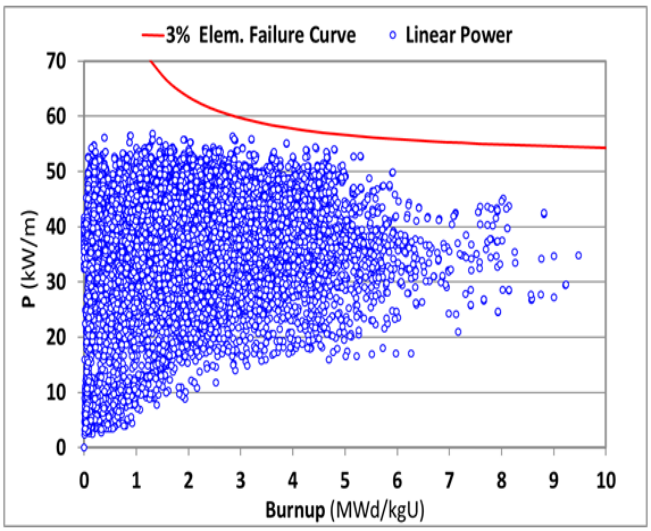


Fig.7. NU+NUE Linear Power

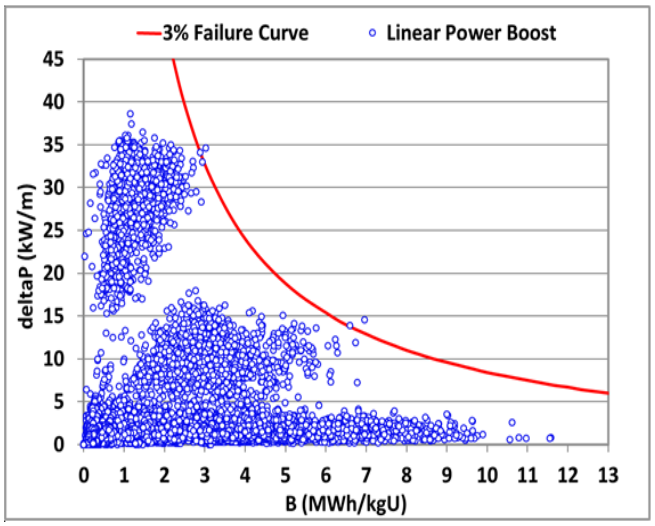


Fig.8. NU Linear Power Boost

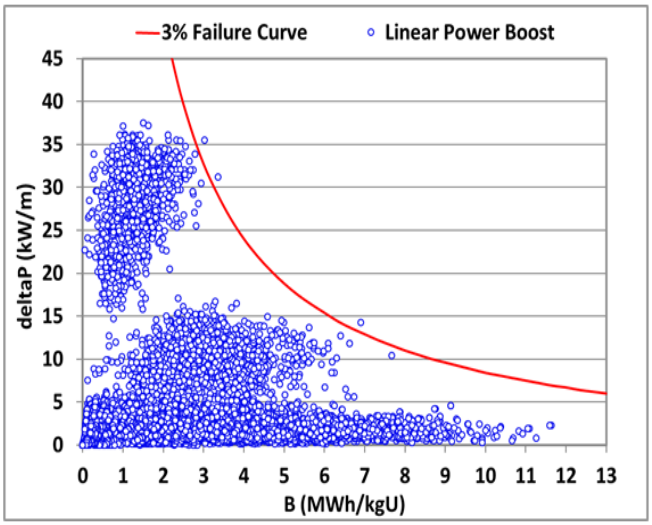


Fig.9. NU+NUE Linear Power Boost

In Fig. 7 there are several (NU+NUE) MOELP values situated closer to the 3% element failure curve [12], than in Fig. 6 where NU OELP distribution is shown. The 3% element failure curves are drawn according to [12], where it is also stated that UO2 fuel may cope with OELP and OELPB values resulting in a defect probability just higher than 3%, but in order to allow provisions for safety margins, the 3% fuel failure curve has been currently used as a reference and it shouldn't be exceeded. It is easy to observe that there are no points overriding the 3% failure curves in both Figs 6 and 7. On the other hand, during refuelling process a bundle shift along the fuel channel may result in linear power increasing between two successive positions.

This linear power increasing is just the MOELPB delivered by DIREN calculations and represented in Figs. 8 and 9, respectively. As a peculiarity, both core sorts considered, the pure NU core and the mixed (NU+NUE) one, supplied the same number of overriding (3 times) on OELPB graphs. Nevertheless, the behaviour of both reactor core types is safe, because the condition to have 3% likelihood of fuel failure asks for simultaneously overriding the 3% failure curves on both OELP and OELPB graphs at a given burnup ([12]). As only the failure curve on OELPB graphs is overridden, while there are no points overriding the failure curve on any OELP graph, this means that the failure of any fuel sort is not expected to happen.

Table 3 synthetizes refuelling burnup simulation results along the considered 710 FPD interval.

Table 3. Refuelling burnup simulation results

Parameter	**NU**	**NU+NUE**
# Full Power Days (FPD)	710	710
# of discharged bundles	10,920	10,544
Uranium mass per bundle (kg)	19.49	19.49
U consumption = #bundles*U	212,864	205,534
Reactor Thermal Power (RTP)	2061.4	2061.4
Average Burnup = RTP*#FPD /	6.88	7.12
Maximum Channel Power (kW)	7094	7099
Maximum Bundle Power (kW)	901	912
Maximum Outer Element Linear	55.8	56.8
Maximum Outer Element Linear	38.6	37.5
Number of points above the 3%	0	0
Number of points above the 3%	3	3
Number of points overriding 3%	0	0

The MOELP value over all (NU+NUE) mixed core bundles is 56.8 kw/m, only 2 % larger than that of pure NU fuelled core, while MOELPB are inversely ordered.

The economics of both considered reactor cores (the pure NU fuelled core and the mixed NU+NUE fuelled one) can be expressed as the fuel burnup, averaged on the 710 FPD of simulations, considering a constantly-supplied thermal power of 2061.4 MW, divided by the cumulative Uranium consumption. The mixed (NU+NUE) fuelled core supplied a slightly improved fuel burnup management through the value of 7.12 MW/kgU, versus 6.88 MWd/kgU characterizing the NU fuelled core

Conclusions

The considered NUE fuel option based on both recycled and depleted Uranium led to promising result regarding the behaviour in normal operation conditions of a CANDU power reactor.

The core calculations results obtained through refuelling burnup simulations for pure NU and mixed (NU+NUE) fuelled options are in good agreement to those supplied by the time-average approximation, this proving the correctness of modelling.

A CANDU core conversion from NU to NUE fuel is possible to be achieved without major power tilts, shaping the imposed NU power envelope and subsequently leading to slightly improvements in the fuel burnup.

Advanced simulations of refuelling operations are still needed to be performed over a considerably larger number of FPD, in order to obtain more accurate values for parameters of interest regarding the fuel burnup performance and nuclear safety.

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