INVESTIGATING THE INFLUENCE OF REFUELING SCHEME PATTERN ON CORE PARAMETERS OF A CANDU REACTOR FED WITH THORIUM-BASED FUEL

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Abstract

Romanian energy sector benefits of an important contribution brought by the two nuclear CANDU units of Cernavoda Nuclear Power Plant (NPP). A Thorium-based fuel design is envisaged in this paper to be used in a generic CANDU power reactor along with some refuelling schemes whose using effects will be revealed. The fuel is a mixture of Uranium and Thorium dioxide with a ratio of heavy element masses (U/Th) of about 0.3. Uranium dioxide contains Low Enriched Uranium (LEU) with 9 wt% enrichment in U235 in order to achieve an initial fissile concentration under 2% per bundle mass. Lattice and core burnup calculations have been performed to find out the refuelling scheme influence on some core parameters like: average discharge burnup, reactivity, bundle consumption, maximum channel and bundle powers along with outer element linear powers. The benefits and drawbacks of every refuelling scheme are revealed.

Keywords: *CANDU, Thorium-based fuel, Refuelling scheme*

Introduction

Romanian energy sector benefits of an important contribution brought by the two nuclear CANDU units of Cernavoda Nuclear Power Plant (NPP). Unit 1 and 2 have been operating since 1996 and 2007, respectively, at high capacity factors and respecting high safety standards. One of the main reasons for such successful operation is the unique CANDU feature of on-power refuelling.

Earlier studies worldwide performed showed that CANDU reactors also have the ability to accommodate a large variety of advanced fuels, apart from the standard one, based on natural Uranium.

A Thorium-based fuel design is envisaged in this paper to be burnt in a generic CANDU power reactor along with some refuelling schemes whose neutronic effects will be revealed.

The actual reloading strategy in CANDU power reactors is based on using of the well-known 8-bundle shift scheme, this assuring a fair compromise between the fuelling machine burden and economics of the Natural Uranium (NU) fuel cycle. On the other side, introducing of a new fuel design with more fissile material than NU fuel one asks for evaluation the suitability of different refuelling schemes.

Fuel Design Description and Methodology Outlines

The fuel is a homogenous mixture of Uranium and Thorium dioxide with a ratio of heavy element masses (U/Th) of about 0.3.

Uranium dioxide contains Low Enriched Uranium (LEU) with an enrichment of 9 wt% in U^{235}, this concentration achieving an initial fissile content of about 1.8 wt% per bundle.

This fuel composition was placed in the 37-rods CANDU standard bundle design, shown in Fig. 1.

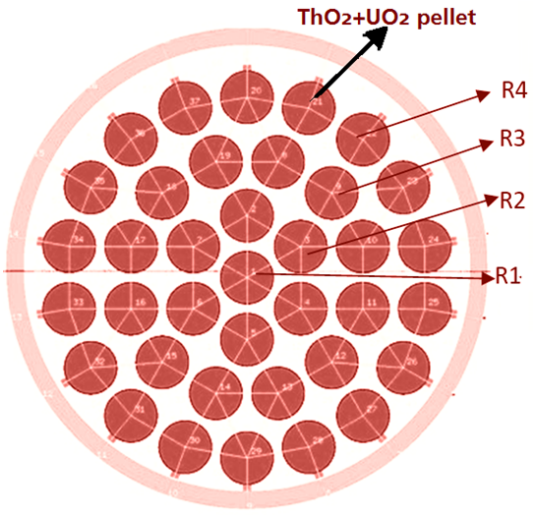


Fig. 1. The 37-rods bundle design filled with Thorium-based nuclear fuel

In the figure above, R1, R2, R3 and R4 denote the central element, inner, intermediate and outer fuel rings.

The Thorium-based fuel characteristics are summarized in Table 1.

Table 1. Thorium-based Fuel Composition

Fuel density (g/cm^3)	**Oxide**	**Oxide concentration in mixture** (wt%)	**Nuclide symbol**	**Nuclide concentration in oxide** (wt%)	**Nuclide concentration in mixture** (wt%)
9.0	ThO_2	67	Th^{232}	87.8	67.7
			O^{16} (in ThO_2)	12.2	9.3
	UO_2 (LEU9%)	23	U^{235}	7.8	1.8
			U^{238}	80.3	18.5
			O^{16} (in UO_2)	11.8	2.7
Oxygen total					***12.0***
Uranium/Thorium Mass Ratio					***0.3***

The following refuelling schemes were considered in the paper: the actual eight bundles shift scheme, the four bundles shift scheme, a mixed 2&4 bundles shift scheme (see Fig. 2) and the two bundles shift per operation scheme, respectively.

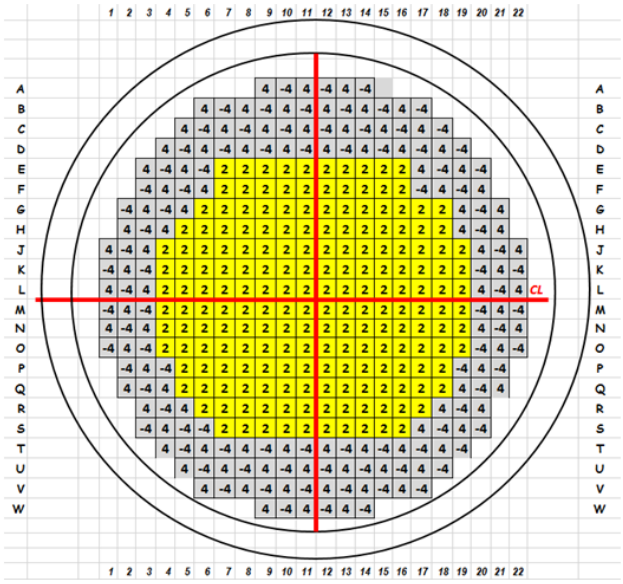


Fig. 2. The mixed refuelling scheme with 2 and 4 bundles shift per operation

In order to find out the influence of the refuelling scheme on the core parameters, lattice and core burnup calculations have been performed for each considered refuelling scheme.

The core parameters envisaged in the study are, as follows: average discharge burnup, core reactivity, daily bundles consumption, maximum channel and bundle powers.

The basic unit of a CANDU reactor is the lattice cell containing the fuel bundle and the associated coolant, the pressure tube, the calandria tube, and a corresponding volume of moderator. The lattice properties depend on the physical dimensions and composition of its materials. Once the burning is started, the amounts of Uranium and Plutonium isotopes will change with respect to the irradiation and, as a result, nuclear properties will change accordingly. Neutronic properties of interest are caught into the macroscopic effective cross sections generated for about 90 burnup steps in the interval 0 - 38 MWd/kgHE (heavy element, HE).

Macroscopic cross sections have been aggregated in specific cross section tables suitable for core calculations. Lattice burnup calculations have been firstly performed with the WIMS-D5B code [1] and the associated IAEA nuclear data library, [2]. Then, the cross section tables were introduced in a standard CANDU 6 core model [3, 4] adapted to the input of DIREN program [5-7]. The time average (TA) calculations have been firstly performed to find out the critical discharge burnup of every refuelling scheme, and to start consequently, the core burnup calculations with refuelling operations' simulation, also known as Core Follow Simulations (CFS). The CFS calculations take into account the refuelling operations explicitly.

Lattice cell results

Infinite multiplication constant evolution versus irradiation is presented in Fig. 3.

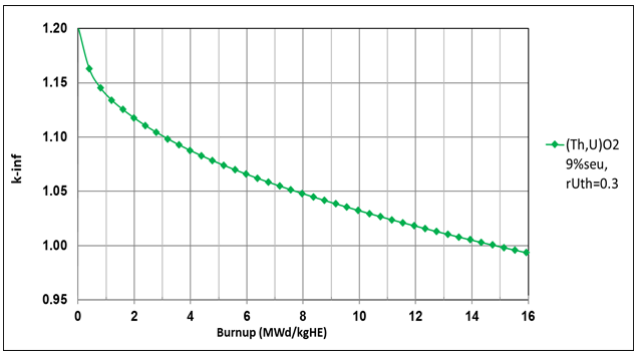


Fig. 3. Infinite multiplication constant versus irradiation

The actual instantaneous exit burnup value for $(Th,U)O_2$ fuel composition given in Table 1 is about 14.9 MWd/kgHE, being found out through interpolation of the values from Fig. 3.

Time Average Core Results

Time average core calculations supplied average discharge burnups (ADBs) on burnup regions, maximum channel and bundle powers along with Zone Control Units (ZCU) reference radial power distribution.

Table 2 presents TA core relevant parameters as follows: Average Discharge Burnup (ADB), k-effective, number of refuelled bundles and channels per one Full Power Day (FPD), maximum channel and bundle powers. It has to be mentioned that ″bs″ abbreviation used in the following denotes the bundle shift scheme.

Table 2. Time-average core results

Config. No.	**Acronym of Refuelling Strategy**	**ADB** (Mwd/kgHE)	**k-eff**	**#Bundles/ FPD**	**#Channels/ FPD**	**Rho** (mk/FPD)	**Max. Channel Power** (kW)	**Max. Bundle Power** (kW)
1	8bs	18.62	0.99992	6.56	0.82	-0.2	6247.6	800
2	4bs	17.93	0.99998	6.83	1.71	-0.09	6202.1	693
3	2&4bs	17.75	1.00003	6.90	2.57	-0.06	6203.1	703
4	2bs	17.68	1.00001	6.93	3.47	-0.04	6268.4	712

The highest ADB is supplied by the actual CANDU standard 8bs scheme, but this result must be carefully taken into account because the time average approximation offers only a rough picture of the reactor core behaviour. Configuration #1 also gives the highest maximum channel and bundle powers in the series, this being an indication that its safety margins are smaller than those corresponding to the rest of configurations.

The last three configurations supply closer results, their ADB being in range of 17.68 - 17.93 MWd/kgHE along with significantly lower channel and bundle powers than those corresponding to Configuration #1.

Core Follow Simulation Results

Following the procedures described in [5-7], the CFS calculations have been performed for every refuelling scheme. Not all the 4 configurations associated to the considered refuelling strategies (see column 1 of Table 2) have succeeded the CFS type of calculation, but only the last three of them. Unfortunately, the 8bs strategy failed in shaping the reference power distribution due to too many bundle and channel power tilts. Therefore, our consequent analysis addresses only Configurations # 2, 3 and 4.

Table 3 presents synthetically the CFS results for Configurations # 2, 3 and 4.

Table 3. Core Follow Simulation (CFS) Results

#	**Parameter**	**Configuration**			**Differences**		
		2	**3**	**4**	**3 vs. 2** (%)	**4 vs. 2** (%)	**4 vs. 3** (%)
		2 bs	**2&4 bs**	**4 bs**			
1	Full Power Days (FPD)	950	950	950			
2	# of Discharged Bundles	5,738	6,216	5,644	8.3	-1.6	-9.2
3	Bundles / FPD	6.04	6.54	5.94	8.3	-1.6	-9.2
4	HE Bundle Mass [kg]	17.05	17.05	17.05	0.0	0.0	0.0
5	HE consumption [kg/FPD]	103.0	111.6	101.3	8.3	-1.6	-9.2
6	Daily Thermal Energy (DTE) = Fission Power (MWt) * 1 day	2,156	2,156	2,156	-	-	-
7	Refuelling Average Burnup (RAB) = DTE/U consumption [MWd/kgHE]	20.94	19.33	21.28	-7.7	1.7	10.1
8	Maximum Channel Power [kW]	7,100	7,098	7,100	0.0	0.0	0.0
9	Maximum Bundle Power [kW]	961	893	957	-7.1	-0.4	7.2
10	Maximum Outer Element Linear Power (OELP) [kW/m]	62.8	58.34	62.5	-7.1	-0.5	7.1
11	Maximum Outer Element Linear Power Boost (OELPB) [kW/m] (see Figs. 4-9)	41	44.2	42.5	7.8	3.7	-3.8
12	Number of points above the OELP fuel failure curve	2	0	0	-	-	-
13	Number of points above the OELPB fuel failure curve	1048	1458	1519	39.1	44.9	4.2
14	Number of points overriding both fuel failure curves	1	0	0	-	-	-

The first comment addresses the number of discharged bundles which is quite different for each bundle strategy. Configuration #4 (that uses 4bs strategy) supplied the lowest fuel consumption (5644 bundles), thus being the best in economic terms. Its heavy element consumption per FPD (full power days of operation) shows the same behaviour, lower by 1.6% and 9% than the other two competing configurations, accordingly to the number of discharged bundles.

A measure of economics through CFS calculations is the so called *Refuelling Average Burnup* (RAB) defined as the average burnup over the simulated period, in our case 950 FPD.

To find out RAB a simple calculation has to be performed. Knowing the thermal energy generated in one FPD through fissions and supposing that the plant is operated at full capacity factor, we can estimate RAB as the ratio of one FPD thermal energy and daily HE consumption.

The results are shown in Table 3, row #7. Again, 4bs strategy supplied the largest value, namely 21.28 MWd/kgHE (larger being better in economics of fuel utilization).

On the other side, it would be worthy to remind that this Thorium-based fuel RAB is about three times larger than that of natural Uranium fuel (about 7-7.3 MWd/kgHE).

It can be concluded that the 4bs refuelling strategy in connection with Thorium-based fuel is more cost-effective than the 2bs and 2&4bs refuelling strategies, but this achievement has to be accompanied by the associated safety analysis regarding the Outer Element Linear Power (OELP) and Outer Element Linear Power Boost (OELPB) that are to be revealed in the following.

OELP and OELPB bring valuable indications regarding fuel behaviour and performances during its residence in the reactor core, therefore these amounts must be carefully evaluated. OELP and OELPB values were obtained using WIMS and DIREN calculations. The WIMS program supplied the radial power distribution (the power fractions) and DIREN calculated the effective bundle power distribution over the reactor core during CFS calculations. Then, using a simple multiplying operation, OELP values were revealed.

In Figs. 4 to 9 the neutronic amounts mentioned above are presented with respect to the burnup, for every of the three selected bundle shift schemes.

As Table 3 reveals (see line #13), in spite the fact that OELP overrides are insignificant, there are many points where OELPB values pass the failure curve thresholds (as can be seen in Figs. 5, 7 and 9). 4bs strategy supplied the highest number of overrides (1519), while 2bs and 2&4bs schemes led to lower numbers. Nevertheless, AECL Design Manual [8] clearly mentions that for a fuel bundle to fail as result as power and power boost increasing conditions, its OELP and OELPB values must override simultaneously the corresponding failure thresholds at a given burnup.

Fortunately, only the 2bs refuelling scheme has one single point on both graphs applying to an effective failure probability of 1%, as can be seen in Fig. 4 (the point corresponds to a burnup of 115.7 MWh/kgHE and a ramped power of 57.08 kW/m, a bit over the limit). As a result, it can be appreciated that the 2&4 bs and 4 bs refuelling strategies are safer than the 2bs one. Taking a look at Figs. 4, 6 and 8, a larger safety margin (between the failure red curve and the green dotted line) can be also observed for the 2&4 bs configuration.

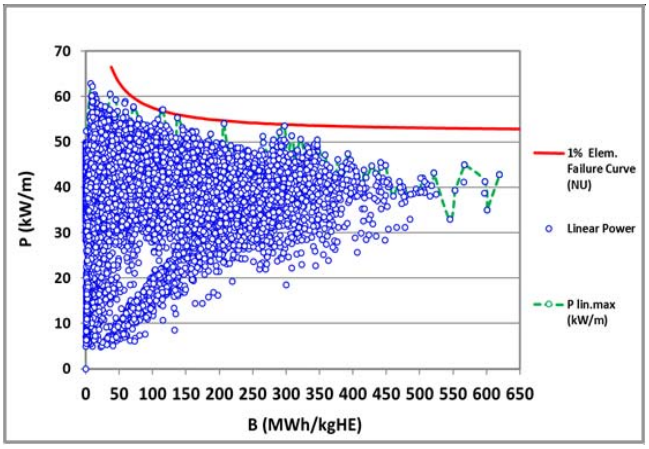


Fig. 4. Outer Element Linear Power, 2 bundle shift scheme

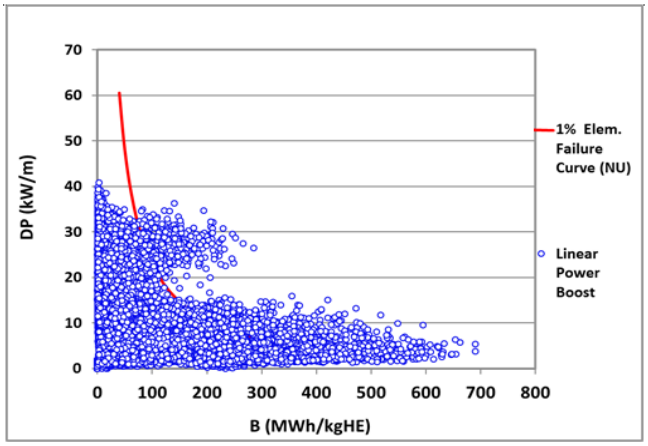


Fig. 5. Outer Element Linear Power Boost, 2 bundle shift scheme.

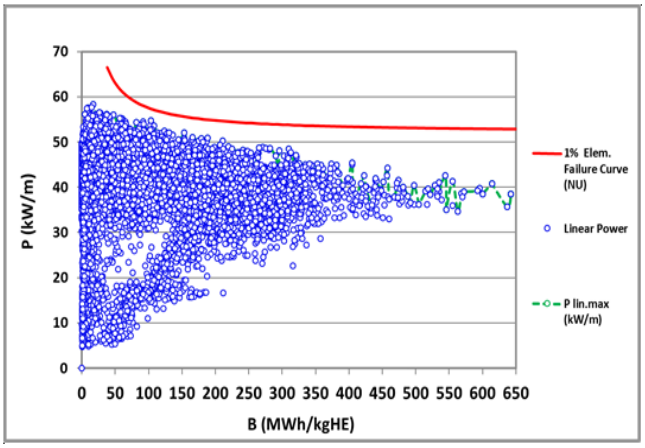


Fig. 6. Outer Element Linear Power, 2&4 bundle shift scheme.

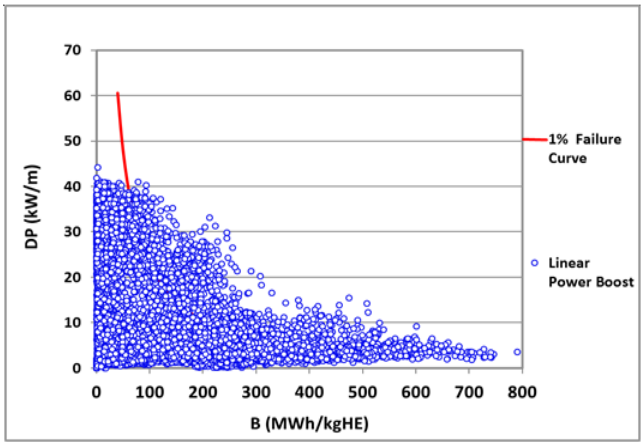


Fig. 7. Outer Element Linear Power Boost, 2&4 bundle shift scheme.

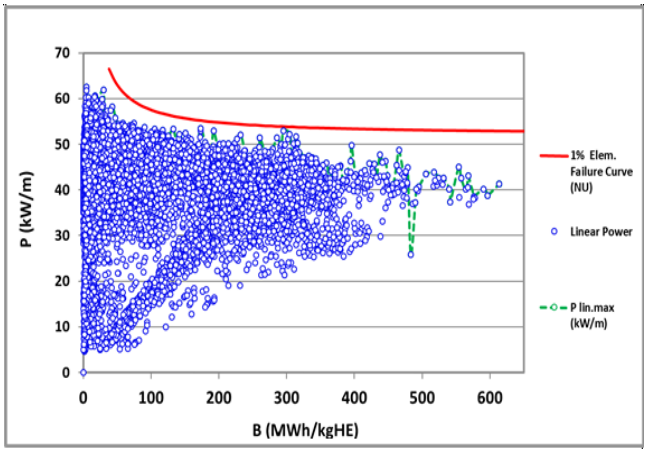


Fig. 8. Outer Element Linear Power, 4 bundle shift scheme.

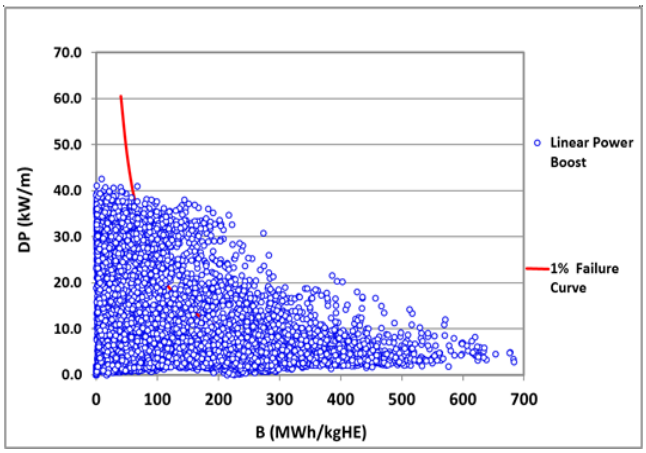


Fig. 9. Outer Element Linear Power Boost, 4 bundle shift scheme.

It can be concluded that there are no serious safety concerns regarding the using of the 2bs, 2&4bs and 4 bs refuelling schemes applied to a CANDU reactor core fed with Thorium-based fuel bundles with an initial fissile concentration of 1.8 wt%.

Moreover, the failure curves taken into account correspond to the natural Uranium fuel, but mixed oxide $(U,Th)O_2$ fuel is expected to have a lesser restrictive failure curve, due especially to the significantly higher melting point of Thorium dioxide.

Conclusions

Thorium-based fuel with an initial fissile content of 1.8 wt% per bundle can be used in actual CANDU reactors in refuelling schemes with 2 and 4 bundle shift per operation, but also in a mixed approach with 2&4 bundle shift refuelling scheme.

The best economic results have been supplied by the 4 bundle shift refuelling scheme, while the mixed approach scheme with 2&4 bundle shift per operation seems to be the safest one in the series, its safety margins associated to the outer element linear powers being the largest.

In order to save Uranium resources and to significantly reduce the amount of radioactive waste produced by the reactor operation, Thorium-based fuel still remain a valuable option for alternative fuel cycles to be used in actual CANDU reactors.

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