CORE NEUTRONIC EFFECTS AT THE USE OF BURNABLE ABSORBERS IN CANDU FUEL BUNDLES

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The paper reveals the core neutronic effects at the use of burnable absorbers (BA) in the central element of CANDU[3] standard (0.7%U235) and SEU-43 (0.96%U235) bundle designs. The calculations revealed burnup and FPD penalties through both lattice and core calculations. The lattice and core results are in good agreement.

Keywords: CANDU, SEU-43, DIREN, burnable absorbers

1. Introduction

It is well known that all CANDU reactors in operation have a positive Coolant Void Reactivity (CVR), i.e. when coolant is lost, the reactivity increases along with the reactor power. This has always been the most important criticisms about CANDU. The overriding of this drawback can be performed using burnable absorbers (BA) in the central element of the fuel bundle, as we demonstrated in [1]. Nevertheless, we haven't analyzed the BA using influence on core parameters, yet. In this paper we present core neutronic effects at the use of BA in the CE of a CANDU standard fuel bundle with 37 rods (entitled NU-37) along with the SEU-43-a CANFLEX[4]-based fuel bundle design with 1.1% enrichment developed in Institute for Nuclear Research (INR) Pitesti. In order to perform CANDU core simulations a 3D diffusion code DIREN, [2] has been developed in INR Pitesti along the years. The simulation of a nuclear power reactor core evolution has always been a major challenge for nuclear engineers. Some enhancements were added to the DIREN code along with a graphic interface in order to give the possibility to simulate CANDU core automatic refuelling operations up to 700 Full Power Days (FPD). The calculations were performed in several configurations of the central fuel element corresponding to the standard design and also to different thicknesses of the absorber layer.

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2. Fuel Designs and Methodology used in Simulation

We chose two fuel bundle designs: the first one is the CANDU standard fuel bundle (referred as "*NU-37*") and the "*SEU-43*"- a CANFLEX based bundle design developed in INR Pitesti, fuelled with Recycled Uranium (0.96% Slightly Enriched Uranium, plus small amounts of U234 and U236, see Table 1). Geometrical characteristics of the two bundles were taken from Ref. [3] and their pictures are shown in Fig. 1, after [4].

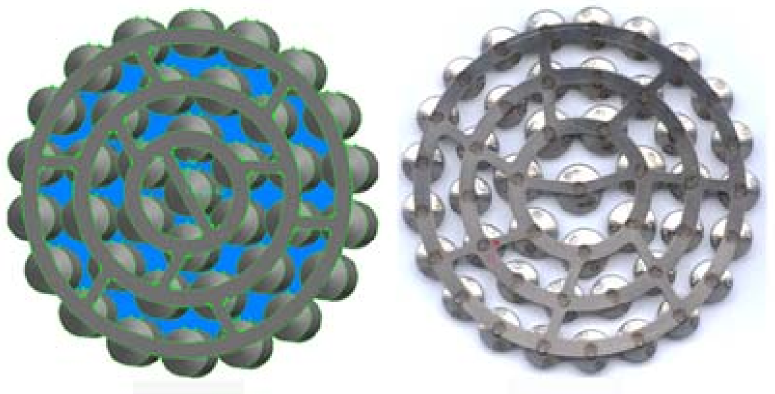

Fig. 1. NU-37 (left) and SEU-43 (right) Fuel Bundles, [4]

In a previous paper [5], we focused on the lattice burnup effects (entitled "*burnup penalties*") induced by BA using in the central element (CE) of the fuel bundle. The *"burnup penalties"* term refers the effects induced by BA on the k-inf multiplication constant values, i. e. the maximum (critical) burnup values at which the fuel lattice still remains critical. In this paper we performed core calculations using the DIREN computer program in the so called "*burnup simulation on time-steps*" in order to find out how much the time until refuelling starting is shortened. This shortening was entitled as "*FPD penalty*". The working configurations were those from [1], the only one difference being the missing of the 3 and 4 mm BA thickness situations. The reason why we eliminated these BA thicknesses was the fact that they are too absorbent and as a result the core couldn't be critical. Figures 2 and Table 1 present the four working configurations corresponding to the CE of NU-37 fuel design. We also mention that the pure Hafnium was chosen as burnable absorber (BA), as in [1].

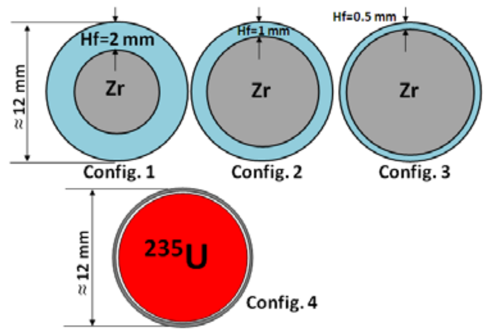

Fig. 2. The four configurations corresponding to the CE of NU-37 fuel design, [5]

Table 1

Working Configurations

Fuel design	**Geometry**	**Configuration** (Case)	**Composition by inner rings**
NU-37	CANDU-37 rods	1 - 3	• CE: Zr rod+ Hf layer of 2, 1, 0.5 mm; • R2,R3,R4: NU in standard pin design (fissile+gap+clad)
		4	• R1,R2,R3,R4: NU in standard pin design (fissile+gap+clad)
SEU-43	CANFLEX-based	1 - 3	• CE: Zr rod+Hf layer of 2, 1, 0.5 mm; R2,R3,R4: 0.96SEU in standard pin design (fissile+gap+clad) + ^{234}U (3.7E-06 nuclei/cm*bn) + ^{236}U (6.5E-05 nuclei/cm*bn)
		4	• R1,R2,R3,R4: 0.96SEU in standard pin design (fissile+gap+clad) + ^{234}U (3.7E-06 nuclei/cm*bn) + ^{236}U (6.5E-05 nuclei/cm*bn)

In Table 1 the following abbreviation were used:

- CE = Central Element
- R1,R2,R3,R4= inner ring from centre to the outermost part of the bundle
- 0.96%SEU = Slightly Enriched Uranium (0.96% U235);
- NU = Natural Uranium (0.72%U235, 99.28% U238).

3. Lattice burnup penalties

Burnup penalties referred in the previous chapter are now expressed as the differences between the Maximum Critical Burnup (MCB)-the value possibly to be attained without using absorbers and the corresponding MCB value at the use of absorbers in the CE. In this respect, the k-infinity values were extracted from [5] and represented in Figs. 3 and 4. They correspond to the four configurations in Table 1: with absorber in the CE (the first three situations) and without absorber in the CE (the fourth situation, which corresponds to the standard design of the CE).

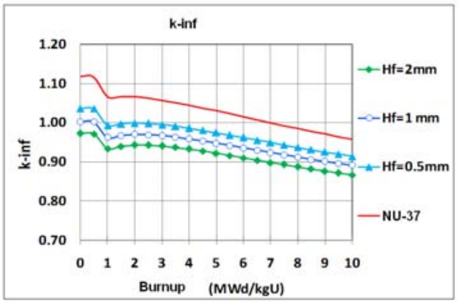

Fig. 3. k-inf evolution for NU-37 fuel design

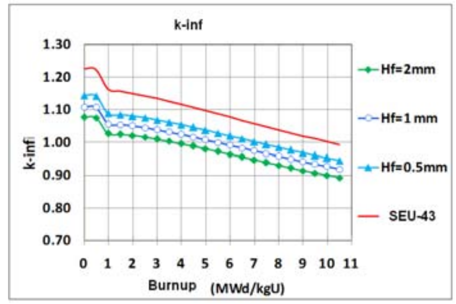

Fig. 4. k-inf evolution for SEU-43 fuel design

As it can be seen, the presence of absorbers in CE of the bundle significantly decreases the lattices' criticality. The most influenced is the NU-37 lattice in case of the thickest absorbent shell (2 mm, green curve on Fig. 3), when the lattice cannot become critical. As opposed, the SEU-43 lattice criticality is less influenced by the absorber using, quite in the case of 2 mm absorbent shell, the lattice remains critical up to 3.5 MWd/kgU, see Fig.4. Tables 2 and 3 offer absolute burnup penalty values as differences between possible MCB and attained MCB and also, relative penalty values for the two fuel designs.

Table 2

Burnup penalties with respect to BA thickness for NU-37 fuel design

NU-37	**Config.2** (Hf=1 mm)	**Config.3** (Hf=0.5 mm)	**Config. 4** (without BA)
Possible MCB (MWd/kgU)	7	7	7
Attained MCB (MWd/kgU)	0.5	1	7
Absolute penalty (Possible MCB– Attained MCB) (MWd/kgU)	6.5	6	0
Relative penalty (%)	92	86	0

Very large penalties induced by BA using at the NU-37 fuel design can be observed and as a result, we conclude that these penalties are not economically acceptable.

Table 3

Burnup penalties with respect to BA thickness for SEU-43 fuel design

SEU-43	**Config.1** (Hf=2 mm)	**Config.2** (Hf=1 mm)	**Config.3** (Hf=0.5 mm)	**Config. 4** (without BA)
Possible MCB (MWd/kgU)	10.5	10.5	10.5	10.0
Attained MCB (MWd/kgU)	3.5	5.5	7.0	10.0
Absolute penalty (Possible MCB– Attained MCB) (MWd/kgU)	6.5	4.5	3.0	0
Relative penalty (%)	65	45.0	30.0	0

Having a higher enrichment (0.96%) SEU-43 fuel design offers smaller burnup penalties at the same configuration than those of NU-37 fuel design. In this respect, SEU-43 fuel design is more suitable to be used in conjunction with burnable absorbers.

4. Core Effects at the Use of BA in NU-37 and SEU-43 Fuel Designs

The price paid to improve nuclear safety using BA in the CE consists in lower burnups, as the lattice calculations showed in Tables 3 and 4, after [5]. The novelty element of this paper consists in core calculations using a 3D diffusion code developed in INR Pitesti (DIREN). The performed core calculations used the "*burnup simulation on time-steps*" option in order to find out how long time the initial fuel loading maintains core criticality and to obtain the so called “*FPD penalties*”, in fact the time until refuelling is mandatory to be started. Specific DIREN inputs have been built for every four configurations in Table 1 and diffusion calculations were started in time steps of 10 days. The core reactivity evolution is presented in Table 4 for both fuel designs.

Only in Configuration 3 (0.5 mm BA thickness) the NU-37 core can become critical, but unfortunately for less than 10 FPD. At the next step, core is strongly subcritical (-9.5 mk), an amount above the Zone Control Units or quite above the usual Adjuster Rods reactivity range.

Taking into account also for the lattice results, it is clear that NU-37 fuel design is not suitable to be used in conjunction with burnable absorbers. The small fissile content of Natural Uranium can assure core criticality only in conjunction with heavy water as moderator and without burnable absorbers.

Core results for NU-37 fuel designs are concordantly to those from lattice calculations where the presence of BA limited the attained MCB to about 1 MWd/kgU, unacceptable from economic reasons.

Table 4

Core reactivity with respect to BA thickness for NU-37 and SEU-43 fuel design

Config.	**NU-37**			**SEU-43**		
	Time (Days)	k-eff	Rho (mk)	Time (Days)	k-eff	rho(mk)
Config. 1 (Hf=2mm)	0	0.96430	-37.0	0	1.06300	59.3
	10	0.95250	-49.9	10	1.04780	45.6
	20	0.95580	-46.2	20	1.04260	40.9
	30	0.95880	-43.0	**130**	1.00230	**2.3**
	40	0.96050	-41.1	140	0.99770	-2.3
	50	0.96090	-40.7	150	0.99310	-6.9

Config. 2 (Hf=1mm)	0	0.98650	-13.7	0	1.08650	79.6
	10	0.97400	-26.7	10	1.07090	66.2
	20	0.97670	-23.9	20	1.06530	61.3
	30	0.97910	-21.3	**170**	1.00310	**3.1**
	40	0.98040	-20.0	180	0.99830	-1.7
	50	0.98040	-20.0	190	0.99350	-6.5
Config. 3 (Hf=0.5 mm)	0	1.00370	**3.7**	0	1.10450	94.6
	10	0.99060	-9.5	10	1.08860	81.4
	20	0.99270	-7.4	20	1.08260	76.3
	30	0.99470	-5.3	**200**	1.00220	**2.2**
	40	0.99550	-4.5	210	0.99740	-2.6
	50	0.99520	-4.8	220	0.99250	-7.6
Config. 4 (without BA)	0	1.02720	26.5	0	1.13370	117.9
	10	1.01630	16.0	10	1.11690	104.7
	20	1.01950	19.1	20	1.11020	99.3
	30	1.02190	21.4	230	1.00670	6.7
	110	1.0041	**4.1**	**240**	1.00160	**1.6**
	124	0.9986	-1.4	250	0.99670	-3.3

On the other side SEU-43 fuel design with an enrichment of 0.96% U235 offers promising results: in Config. 3 conditions (0.5 mm BA thickness) reactor core remains critical up to 200 Full Power Days (FPD), see Table 4, when a reactivity value of +2.2 mk is reached. Face to 240 FPD in the SEU-43 standard design of the CE (no BA), the relative time penalty is only 16% (40/240*100). Consequently, the SEU-43 relative time penalties for Config. 1 to 4 are: 45%, 29%, 16% and 0%. These relative values are also in good agreement to those from lattice calculations (see Table 3, the last row) where relative burnup differences were 60%, 45%, 30% and 0.0%, respectively. It should be noticed the presence of the same decreasing amount (about 15%) between two consecutive configurations. The systematic shifting (also of 15%) between two correspondent configurations can be explained through the different modelling methods in lattice and core computer programs (lattice modelling neglect the leakage, but core takes it into account). Anyway, the results can be considered encouraging and must constitute a start point for further (already appointed) core refuelling analyses.

5. Conclusions

The NU-37 fuel design based on the standard CANDU 37-rods fuel bundle with Natural Uranium (0.7%U235) is not suitable to be used in conjunction with burnable absorbers (BA).

Burnup penalties at the use of BA in NU-37 fuel bundle are too large (above 86%), therefore being economically unacceptable.

SEU-43 fuel bundle fuelled with Recovered Uranium (0.96%U235) is a promising option to be used with small amounts of BA.

SEU-43 relative burnup penalties at the BA using range from 60% to 30%, accordingly to the working configurations.

Core calculations showed a 15% decreasing step in relative FPD penalties while the same relative difference between two consequent configurations was found out in k-eff lattice calculations.

The fair agreement between lattice and core results constitutes a starting point for further core refuelling simulations.

Nomenclature

BA = Burnable Absorber(s)
CVR = Coolant Void Reactivity, often VR=Void Reactivity
FPD = Full Power Days
MCB = Maximum Critical Burnup
NU-37 = Natural Uranium fuel bundle with 37 equal rods
SEU-43 = Slightly Enriched Uranium fuel bundle with 43 rods, based on CANFLEX geometry

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