VOID REACTIVITY REDUCTION IN CANDU REACTORS USING BURNABLE ABSORBERS AND ADVANCED FUEL DESIGNS

Iosif PRODEA[1], Cristina Alice MĂRGEANU[2], Andrei RIZOIU[3], Ilie PRISECARU[4], Nicolae DĂNILĂ[5]

Este binecunoscut faptul ca reactorul CANDU are coeficientul de vid al reactivității pozitiv (CVR), ceea ce constituie o critică importantă la adresa acestuia. Inovații recente bazate pe utilizarea unui strat subtire de Hafniu absorbant în pinul central au fost aplicate cu succes la proiectul ACR (Advanced CANDU Reactor). Obiectivul lucră este de a analiza efectele neutronice din celula elementară de combustibil la aplicarea unor astfel de metode de reducere a CVR. Au fost alese spre comparație trei proiecte de celule elementare de combustibil: ACR-1000TM, RU-43 (dezvoltat în SCN Piteşti) şi combustibilul CANDU standard. A fost, de asemenea evaluat efectul adaugă de grafit ca absorbant în diferite locații din fascicul. Calculele WIMS au aratat ca proiectul absorbantului cu Hafniu dispus sub forma unui strat subțire la periferia pinului central este capabil să furnizeze ținta dorită de reactivitate negativă cu mai mare acuratete la proiectul ACR-1000 decât la celelalte două proiecte de combustibil.

It is very well known that the CANDU® reactor has positive Coolant Void Reactivity (CVR), which is an important criticisms about CANDU. Recent innovations based on using of a thin absorbent Hafnium shell in the central bundle element were successfully been applied to the Advanced CANDU Reactor (ACR™) project. The paper's objective is to analyze elementary lattice cell effects in applying of such methods to reduce CVR. Three basic fuel designs in their corresponding geometries were chosen to be compared: the ACR-1000^{TM}, the RU-43 (developed in INR Pitesti) and the standard CANDU fuel. The Graphite absorber influence on void effect was also evaluated. The WIMS calculations proved the Hafnium absorber suitability (in the latest "shell design") to achieve the negative CVR target with a great accuracy for the ACR-1000 fuel bundle design than the other two projects.

Keywords: ACR, CANDU, CVR, burnable absorber

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1. Introduction

All CANDU nuclear power reactors in operation until now 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. A short explanation of this phenomenon can be found out in the pressure-tube design of CANDU and the effects of changes in neutron spectrum upon Loss Of Coolant Accident (LOCA). In pressure-tube reactors, the loss of coolant is not accompanied by a loss of moderator. Moreover, the coolant volume is a small fraction of the moderator volume; therefore the reduction in moderation is much too small to guarantee a negative CVR. To override this drawback, the CANDU trademark owner-AECL proposed some modalities to reduce the CVR to zero and even to a slightly negative value. Most of them are based on placing an absorbing material in the central bundle element and also, on reducing the moderator amount in the elementary lattice both by reducing the lattice pitch and increasing the gap space between the calandria and the pressure tube, [1]. The above methods have together and successfully been applied to the latest Advanced CANDU Reactor (ACR-1000) project, [1].

The paper's objective is to analyze elementary lattice cell effects in applying the above methods to reduce CVR for three basic fuel designs in their corresponding geometries: the ACR-1000, the RU-43 (developed in INR Pitesti and based on the using of Recycled Uranium) and the standard CANDU fuel, with Natural Uranium (NU). A special attention is paid to the current AECL central pin innovative design [1], based on using Hafnium in as a thin shell surrounding the central element, see Fig.1 and 2.

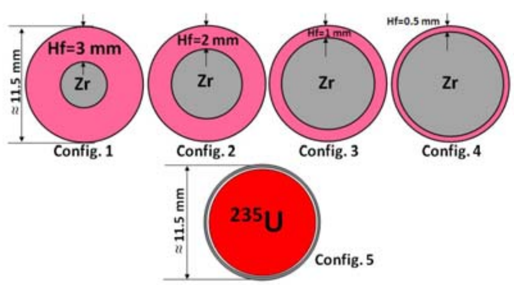

Fig. 1. CANDU-6 central element design (at scale)

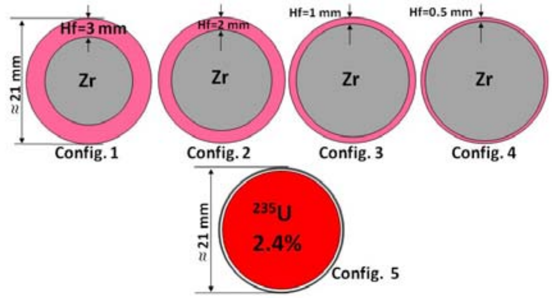

Fig. 2. ACR-1000 central element design (at scale)

2. Considered Fuel Designs and Elementary Cell Characteristics

Three fuel designs were chosen to be analyzed and find out the suitability of the central element "Hafnium shell innovation" to meet the CVR reduction. They are presented below, in Table 1, followed by a short description. The ACR-1000 design retains many of CANDU design key elements, adding some innovative features, which allow the using of low-enriched uranium (LEU) with light-water coolant in a compact D2O moderated lattice, [1]. The new ACR-1000 central pin geometry design was also applied to the other two fuel designs #2 and #3, see Table 1.

Table 1

Considered Fuel Designs

Fuel #	Fuel design	Lattice Pitch	Geometry	Composition by Inner Rings
1	ACR-1000™ (AECL)	24 cm	Modified CANFLEX® 43 rods	R1[a]: Zr Rod+ Hf shell of 1 to 4 mm;R2, R3, R4: LEU[b] (2.4% ^{235}U).
2	RU-43 (INR Pitesti)	28.575 cm	CANFLEX 43 rods	R1: Zr Rod + Hf shell of 1 to 4 mm R2, R3, R4: SEU[c] (0.96% ^{235}U) + + ^{234}U (3.7E-06 nuclei/cm*bn) + + ^{236}U (6.5E-05 nuclei/cm*bn); 1 bn=10^{-24} cm^2
3	NU	28.575 cm	CANDU-37 rods	R1: Zr Rod+Hf shell of 1 to 4 mm; R2, R3, R4: NU[d] (0.71%^{235}U)

[a] R1 to R4 denote the fuel rod "rings" starting from the bundle central element;
[b] LEU = Low Enriched Uranium;

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[c] SEU = Slightly Enriched Uranium;
[d] NU = Natural Uranium.

The corresponding cell geometries of the above fuel designs are presented in Fig. 3, after [2].

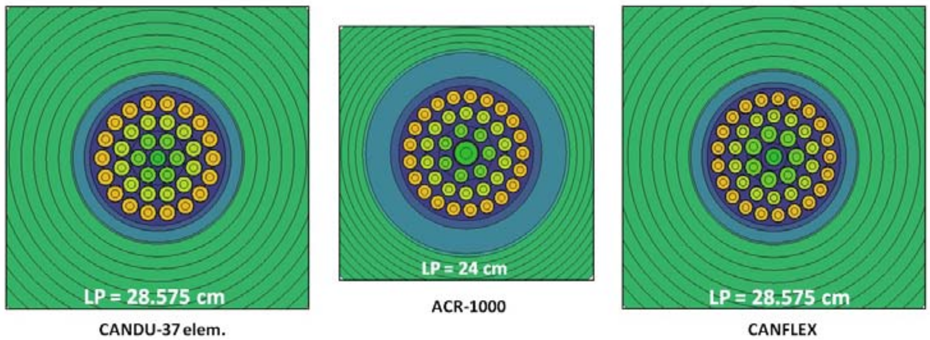

Fig. 3. Considered elementary cell geometries, [2]

The RU-43 fuel was developed by INR Pitesti and it is based on using the Recycled Uranium (RU) in a CANFLEX-based bundle geometry with some quantities of U234 and U236, see Table 1. The U235 enrichment was assumed to be 0.96%. It is very well known that the CANDU-6 standard fuel uses Natural Uranium (NU) as fuel, therefore we won't insist on describing it.

3. Methodology Outlines

The main tool used in calculation was the transport (DSN) code WIMS, version D5B, [3] and an updated library, [4]. As it is very widespread in transport calculations we won't insist on its description. The void effect was estimated in five configuration cases for each type of the three fuel designs, as it is shown in Table 2, below. In the first four cases (1 to 4) the compositions are the same only for the outer rings, the central one having no fissile material and different thicknesses for Hafnium shell surrounding the Zirconium central rod. The fifth configuration corresponds to the standard fuelling situation i.e. the fuel composition is the same overall the fuel rings, and all fuel pins have the standard design (fuel rod, gap space and Zircaloy sheath).

On the other side, since no 3-D details can be modelled with WIMS, the loss of coolant is simulated by simply reducing the coolant density, homogeneously:

$$d^{void} = d^{ref} \cdot \left(1 - \frac{f}{100}\right) \tag{1}$$

where d^{ref} and d^{void} are the reference and accident coolant densities, while f is the void fraction, in %.

Table 2

Considered Working Configuration Cases for Each Fuel Design

Fuel#	**Fuel design**	**Geometry**	**Case**	**Composition by Inner Rings**
1	ACR-1000^{TM}	Modified CANFLEX$^{®}$ 43 rods	1 to 4	• R1: Zr Rod+ Hf shell of 1,2,3 and 4 mm thickness • R2,R3,R4: 2.4% LEU
			5	• R1 to R4: 2.4% LEU in standard fuel pin design
2	RU-43 (INR Pitesti)	CANFLEX 43 rods	1 to 4	• R1: Zr Rod + Hf shell of 1,2,3 and 4 mm thickness • R2,R2,R3: 0.96%SEU+^{234}U+^{236}U
			5	• R1 to R4: 0.96%SEU+^{234}U234+^{236}U in standard fuel pin design
3	NU	CANDU-37 rods	1 to 4	• R1: NU+Hf shell of 1,2,3 and 4 mm thickness • R2,R3,R4: NU
			5	• R1 to R4: NU in standard fuel pin design

Though this 1-D homogenous coolant model is less descriptive than a 3-D one, the gross reactivity effects were fairly estimated in a previous paper [5]. This time, we have to evaluate the Hafnium thickness influence on **V**oid **R**eactivity (**VR**) given by its classic formula from Eq. (2):

$$VR\,(mk) = \rho^{void} - \rho^{ref} = \left(\frac{1}{k_{eff}^{ref}} - \frac{1}{k_{eff}^{void}} \right) \cdot 1000 \qquad (2)$$

where k_{eff}^{ref} and k_{eff}^{void} are the reference (cooled) and "voided" cell neutron effective multiplication factors. The VR will be presented as function of void fraction and also, as function of Hafnium shell thicknesses of the central pin at different burnups.

4. Hafnium central element shell design influence on Void Reactivity

The paper results are presented in form of Void Reactivity (the same as CVR, CVR≡VR for convenience) variations with respect to the void fractions, tracking the Table 2 cases. Results from fresh and 3,500 MWd/tU burnups are presented in Figures 4 to 9. For ACR-1000 fresh fuel cell, all Hf shell thicknesses

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(1-4 mm) used in calculations, lead to a negative VR throughout the ten void fractions.

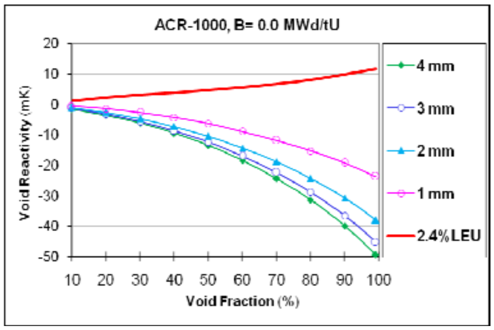

Fig. 4. ACR-1000 CVR for a fresh cell

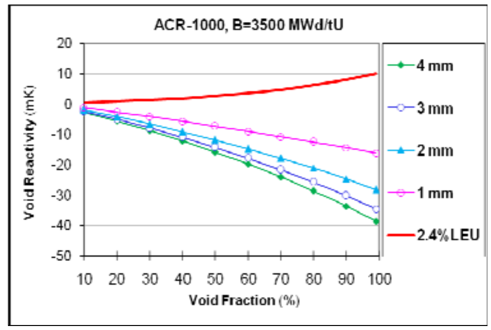

Fig. 5. ACR-1000 CVR for 3,500 MW/tU

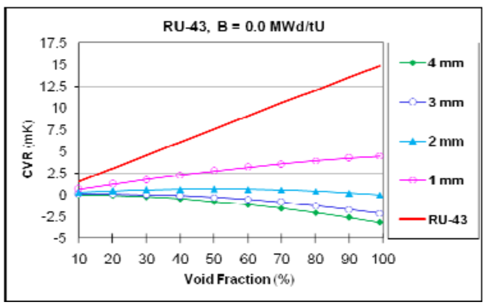

Fig. 6. RU-43 CVR for a fresh cell

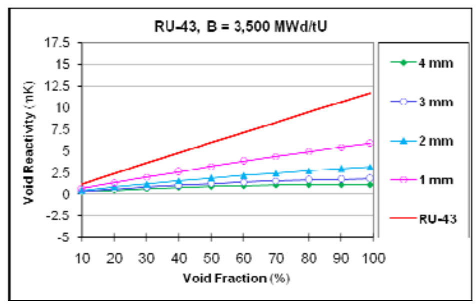

Fig. 7. RU-43 CVR for 3,500 MW/tU

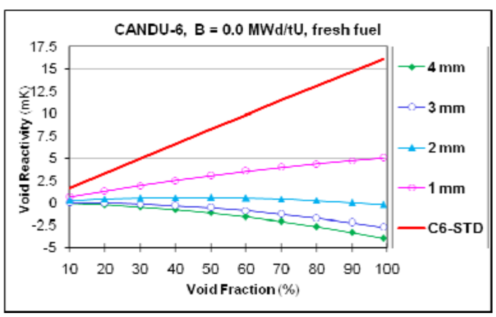

Fig. 8. NU CVR for a fresh cell

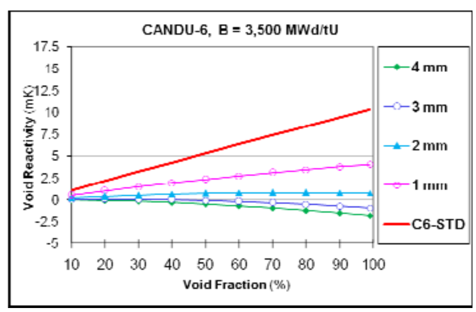

Fig. 9. NU CVR for 3,500 MW/tU

As the central pin composition is changing in 2.4%LEU, the VR immediately rises to positive values (thicker red lines), in both fresh and HOC conditions. The decreasing of the VR with respect to void fractions and also with respect to Hafnium shell thickness is easy visible. For RU-43 and CANDU-6 the same better behaviour is shown in Fig. 6 to 9 for the cases 1 to 4 (Hf "shell design") as opposed to the case 5 where a standard design for central pin is used (red thicker lines). A coarse Hf shell thickness of 2 mm is sufficient in maintaining the CVR near to zero.

5. The using of Graphite as burnable absorber

This way to reduce CVR has been proposed by B.J. Min et al in [6]. Earlier studies [7], proposed using of depleted Uranium as burnable absorber but economic penalties determined renouncing to this method. As result, the Graphite absorber has been promoted in a geometry as in Fig. 10, where it is able to action both as moderator and reflector in normal operation conditions and also, as absorber in accident conditions.

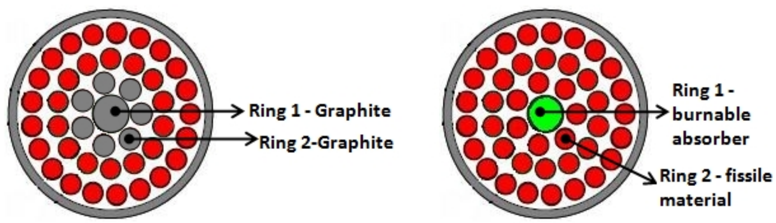

Fig. 10. ACR bundle with Graphite (left) and burnable absorber (right)

The Graphite influence on VR is shown in Figures 11 and 12 for ACR-1000 and CANFLEX bundle geometry.

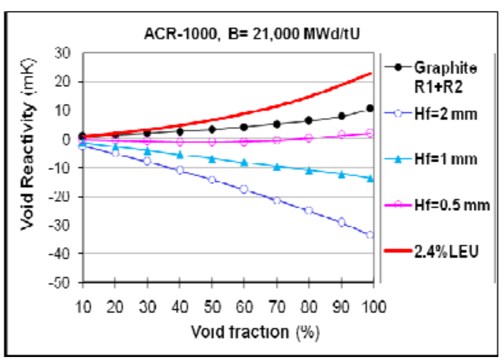

Fig. 11. Graphite Influence on VR, ACR-1000 fuel cell, 21 MWd/kgU

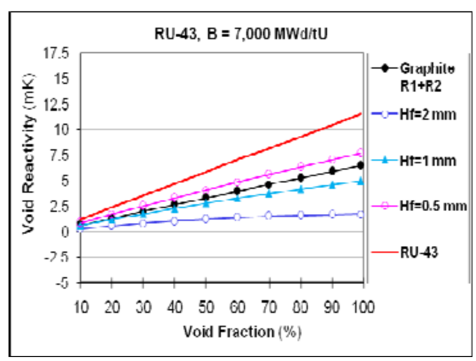

Fig. 12. Graphite Influence on VR, RU-43 fuel cell, 7 MWd/kgU

A significant reduction of VR can be observed in Figures 11 and 12 at the using of Graphite inside of central and first fuel ring elements (see black lines) face to standard fuel design (red line curves). This result qualifies the Graphite as a possibility to reduce CVR in CANDU fuel designs.

6. Conclusions

1) The void effect of the CANDU fuel bundle designs can be significantly reduced by using of burnable absorbers (like Hafnium and Graphite) and advanced designs of the central element.

2) The so-called "Hafnium-shell" design of the central element supplies the best results in the case of ACR-1000 bundle geometry, where a shell thickness up to 2 mm meets a desired negative CVR target.

3) RU-43 and NU fuel designs showed a significantly improved CVR control for Hf shell thicknesses of 2-3 mm.

4) If the paper's results will be confirmed through specific experiments, then it could open the CANDU project way to be accepted in countries with strong nuclear regulation requirements (like USA and Germany) or in other states where, by time, the regulations are becoming more and more restrictive.

Nomenclature

CVR = Coolant Void Reactivity, often VR=Void Reactivity
HOC = Hot Operation Conditions
VR ≡ CVR

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