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VOID REACTIVITY EVALUATION USING HAFNIUM ABSORBER IN ADVANCED CANDU FUEL CELLS

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Lucrarea analizează efectul de vid al unor celule ACR-1000, în cazul utilizării Hafniului drept absorbant consumabil în combustibil. În cadrul noului proiect ACR-1000 se propune utilizarea Hafniului într-o nouă geometrie pentru elementul combustibil central. S-a găsit că, în prezenţa Hafniului în elemental combustibil central, efectul de vid scade cu gradul de golire şi creşte cu gradul de ardere. Calculele au fost efectuate cu o versiune mai nouă a codului WIMS (WIMSD5B furnizat de către NEA Data Bank) şi cu cea mai recentă versiune a bibliotecilor de date nucleare WIMS bazate pe ENDFB-VII, furnizate de către AIEA Viena.

This paper analyzes the Hafnium based burnable absorber influence on Void Reactivity (VR) for a proposed ACR-1000 cell design. The calculations were performed using an updated version of the WIMS code and also the newly ENDF/B-VII based WIMS library. The VR decreases with respect to void fractions but also increases as fuel burns-up. The main result consists in finding out of appropriate Hafnium shell thicknesses supplying a slightly negative VR for each burnup.

Keywords: ACR-1000, Void Reactivity, Hafnium, WIMS, ENDF/B-VII

1. Introduction

It is important to stress that the goal of this paper is fully educational, since the performed studies will help the main author to accomplish his PhD thesis. We only intend to provide a better insight and promotion of the ACR-1000™ concept among the university environment, without any competing of the cited trademarks.

The ACR-1000™ is the nowadays topmost AECL power reactor design developed to address the increasingly competitive world nuclear power market. AECL has adapted the successful features of CANDU®[5] reactors to establish the Generation III+ Advanced CANDU Reactor (ACR™) technology, [1]. The ACR-

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1000 uses the known successful CANDU design elements: horizontal fuel channels, simple fuel bundle design, on-power refueling, separate low-pressure and temperature heavy water moderator providing an inherent emergency heat sink. The ACR-1000 uses the low-enriched uranium (LEU) fuel cooled by pressurized light water, leading to a more compact core configuration and higher steam pressure to improve the thermodynamic efficiency, [1]. In order to reduce the positive Coolant Void Reactivity (CVR) - the major drawback of classical CANDU (6 and 9 versions), AECL proposed several new fuel designs based on both new fuel pin geometry and the use of burnable absorbers.

2. The new ACR-1000 elementary cell characteristics

The ACR-1000 design retains many of CANDU design key elements, adding some innovative features, which allows the using of low-enriched uranium (LEU) with light-water coolant in a compact D2O moderated lattice. Ref.[1] pointed out that the ACR is designed to operate with small negative reactivity feedback coefficients, including the reactivity feedbacks due to changes in coolant density, coolant temperature, fuel temperature and reactor power from nominal operating conditions. These valuable features were obtained after some geometric adaptations of the calandria and pressure tube diameters. In fact, ACR-1000 calandria diameter became about 1.4 cm thicker than the CANDU-6 one. The higher coolant temperature and pressure requested a thicker and stronger pressure tube, accordingly. We took the ACR-1000 fuel channel design data from [2]. Essentially, this is a modified CANFLEX® fuel bundle, where all fuel elements have the same diameter, excepting the central one which is significantly thicker, about twice than the original CANDU-6 one. Its radius was calculated using geometric considerations. The U235 enrichment was assumed to be 2.4% in all fuel elements excepting the central one where no fissile material is present but only a central rod of Zirconium surrounded by a thinner Hafnium shell, as it was suggested in a recent paper [3]. Figure 1 shows the new ACR-1000 central pin geometry.

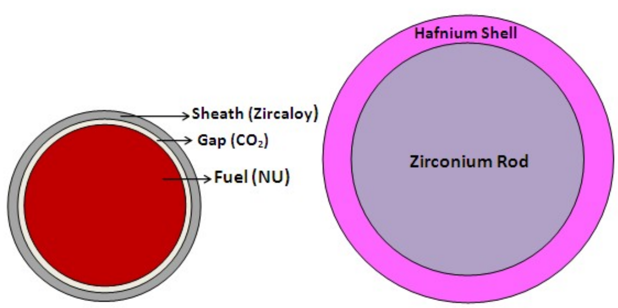

Fig. 1. CANDU-6 (left) and ACR-1000 (right) Central Fuel Pin Design

Remember that older ACR central pin fuel designs were based on the using of Natural Uranium (NU) and Dysprosium-Gadolinium-Zirconium mixture [1], while the current design from [3], proposes a simplified geometry consisting in a Zirconium rod encapsulated in a Hafnium tube. The role of Hafnium as burnable absorber, able to reduce CVR will be analyzed in the next chapter. A schematic representation of the ACR-1000 elementary cell is shown in Figure 2, taken from [1].

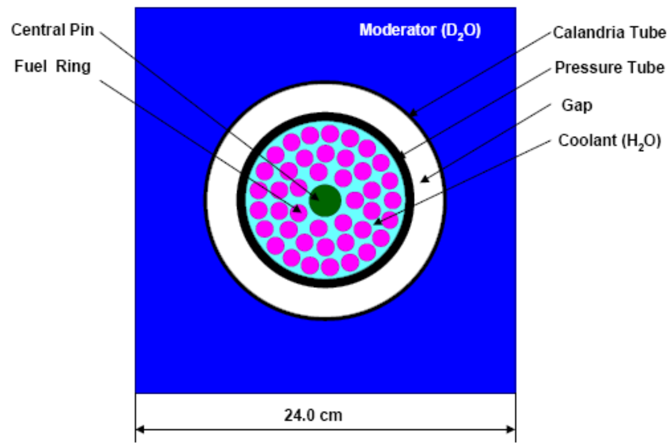

Fig. 2. ACR-1000 elementary cell, [1]

3. Methodology outlines

The updated 1-D transport code WIMSD5B [4],[5] was used to estimate the void effect in five ACR-1000 fuel cells designs, both in "cold" and "hot" conditions. The fives ACR-1000 WIMS input data files differ basically through the thickness of Hafnium shell in the central pin, see Fig. 1. Based on suggestions from [3] we choose five values for this parameter: 0.5, 1.0, 2.0, 3.0 and 4.0 mm. It is worthy to remind that the CANDU fuel channels are horizontal and a **L**oss **O**f **C**oolant **A**ccident (**LOCA**) usually leads to lowering the liquid level in the channel. Since no 3-D details can be modeled with WIMS, the loss of coolant is simulated by simply reducing the coolant density as below:

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

where:

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

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 [6]. This time, we have to evaluate the Hafnium thickness influence on **V**oid **R**eactivity (**VR**) given below by 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 thickness of the ACR-1000 central pin at different burnups.

Regarding Hafnium capability to be used as burnable absorber, it should be pointed that IAEA Nuclear Data Section has released an updated version of the WIMS Library, [7]. It is based on Evaluated Nuclear Data Files, version VII (ENDF/B-VII) and contains valuable data for all burnable isotopes of Hafnium. These data are summarized in Table 1 and the main features in ACR-1000 WIMS modeling used in this paper are presented below:

- the type of fuel cell is cluster (CANDU fuel bundle);
- the solving method is Discrete Sn;
- the transport equation is solved for 69 energy groups, 44 thermal and 25 fast;
- the cell parameters are calculated for two coarse energy groups, 1-44 (thermal) and 45-69 (fast);
- the number of mesh intervals is 47;
- 9 annular regions, 5 containing burnable materials;
- the burnup calculation consists of several steps of 70 days each, a power density of 50 kW/kgU and a final burnup of 28,000 MWd/tU which is only a hypothetical burnup for a CANDU-6 reactor; however it is achievable value for ACR-1000 fueled with 2.4 -3.7% LEU (Low Enriched Uranium), as shown in [3];
- 13 different materials, from which 4 are fuel materials;
- the fresh cell temperatures were 293.15 K for fuel, coolant and moderator;

- the hot cell temperatures were 1283.15 K (fuel), 583.15 (coolant) and 341.15 (moderator).

Table 1

Hafnium Isotopes Characteristics in IAEA WIMS Library, [7]

Z-Symbol-A	Library ID	Atomic weight (amu)	NF	Temp. (K)	Natural abundance (%)	Sig0 (barns)	Description	Evaluated nuclear data source
72-Hf-176	2176	175.941	1	293 700 1100	5.206	1000	Hafnium-176 (burnable absorber)	CENDL-3
72-Hf-177	2177	176.943	1	293 700 1100	18.606	1000	Hafnium-177 (burnable absorber)	CENDL-3
72-Hf-178	2178	177.944	1	293 700 1100	27.297	500	Hafnium-178 (burnable absorber)	CENDL-3
72-Hf-179	2179	178.946	1	293 700 1100	13.625	1000	Hafnium-179 (burnable absorber)	CENDL-3
72-Hf-180	2180	179.947	1	293 700 1100	35.1	500	Hafnium-180 (burnable absorber)	CENDL-3
72-Hf-nat	178	178.487	0	293 600 900	100	500	Natural Hafnium (unburnable)	CENDL-3

Z=Atomic number; A= Atomic weight;
NF=WIMS Library trigger: 0-no resonance table; 1- non fissile with resonance tables
Sig0: Reference Bondarenko cross section [barns]
CENDL = Chinese Evaluated Nuclear Data Library

3. Results and discussions

The paper results are presented in form of ACR-1000 cell **V**oid **R**eactivity (**VR**) variation with respect to void fraction for different burnups and Hafnium central pin shell thicknesses.

In Figures 3, 4 and 5 results from fresh, 3500 and 7000 MWd/tU burnups are presented. No significant differences are visible. A Hafnium shell of about 0.5 mm thickness is sufficient to achieve a negative VR throughout the ten void fractions. The decreasing of VR with respect to void fractions and also with respect to Hafnium shell increasing is visible.

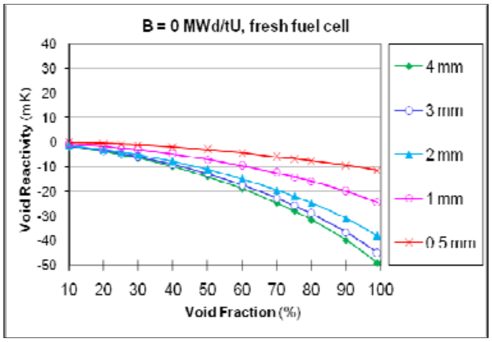

Fig. 3. ACR-1000 Cell VR for a fresh cell

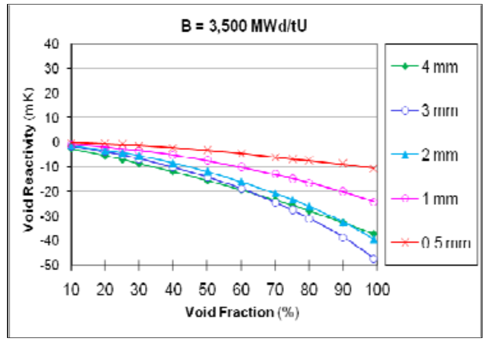

Fig. 4. ACR-1000 Cell VR for 3,500 MW/tU

As burnup increases over 14,000 MWd/TU the VR behavior is changing and it is illustrated in Fig. 6 and 7. This time, a thicker Hafnium shell from 1 to 2 mm is necessary to obtain the desired slightly negative VR (see pink line in Fig. 6 and blue-triangle line in Fig. 7). Thus, at highest studied burnup of 28,000 MWd/tU (still achievable by 2.4-3.7% LEU fuel), the needed Hf shell thickness increased to 3 mm (blue circle-line) in order to maintain a minimum negative VR.

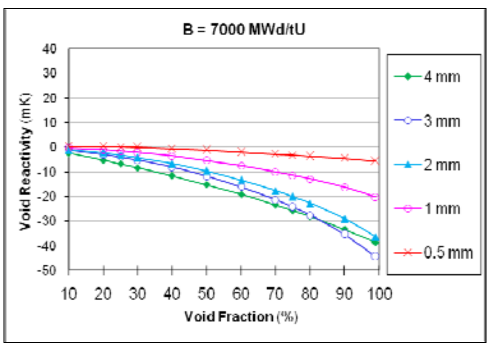

Fig. 5. ACR-1000 Cell VR for 7,000 MW/tU

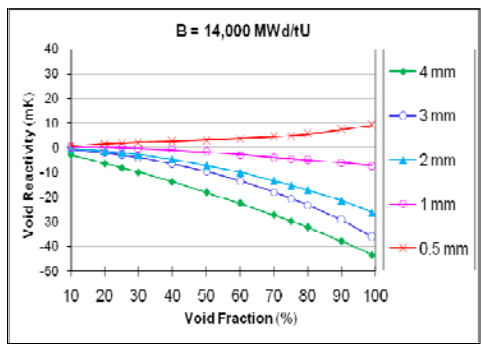

Fig. 6. ACR-1000 Cell VR for 14,000 MW/tU

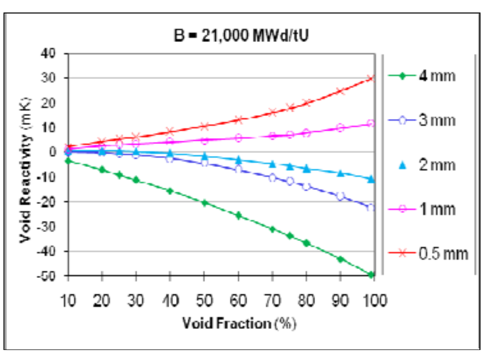

Fig. 7. ACR-1000 Cell VR for 21,000 MW/tU

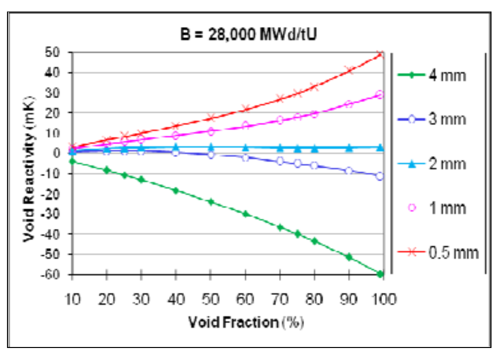

Fig. 8. ACR-1000 Cell VR for 28,000 MW/tU

The explanation of these phenomena is quite simple. The Hafnium isotopes burn out more quickly than the fuel undergoes this process and the reactivity can increase more rapidly when cell is voided in the same manner. As a result, a thicker and thicker Hafnium shell is necessary to tailor the initial proposed VR target. We mention that this negative VR target value was in the range of -10.0 to 0.0 mk.

In spite of the fact that our exploratory values for Hafnium shell thickness were spread in a larger interval than that suggested in [3], the WIMSD5B calculations led us, finally, to the same suitable Hafnium shell thickness from 1 to 3 mm. We can conclude that these last values are in good agreement to those reported in the recent AECL paper [3], where Hafnium shell thicknesses from 1.5 to 3 mm fulfilled the negative VR requirements. It should also be mentioned that AECL used an internationally recognized IST (Industry Standard Toolset) version of WIMS code and therefore, we consider our results being reasonable.

To accomplish our results comparison to those from [3], we represented in Fig. 9 the spatial and spectral changes of the neutron flux inside the fuel bundle at a 99% void fraction (in fact a "complete" LOCA). Nearby, in Fig. 10, the analog representation from [3] was reproduced. The flux shape agreement is evident and the explanation is also given in [3]: only a small fraction of the the thermal neutrons coming from moderator reaches the central pin during normal operating conditions because of the absorption and scattering effects that occur in the outer fuel pins and in the H_2O coolant. This shielding effect is reduced during LOCA due to the absence of the H_2O coolant. The thermal neutron flux level decreases in the outer-most pins and increases towards the central pin upon LOCA as both Fig. 9 and 10 reveal.

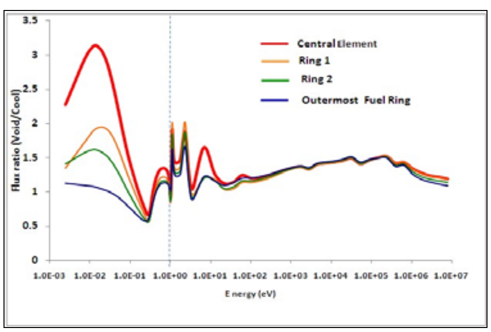

Fig. 9. Spatial and spectral flux changes at 21,000 MWd/tU and a Hf thickness of 4 mm (WIMSB5 calculations)

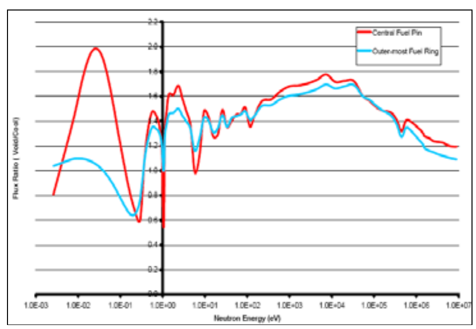

Fig. 10. Spatial and spectral flux changes, [3] (WIMS-AECL 3.1 calculations)

This is the reason why the burnable absorber is placed in central pin of the bundle, to determine an increased neutron absorption which pulls down the Void

Reactivity (VR). On the other side, the fissile material was fully removed from central pin of the bundle due to the same reason: to avoid the neutron multiplication in this high flux region in accident conditions.

Regarding the differences between flux ratio in the central pin (red curves in Fig. 9 and 10), they could be explained by the using of different Hafnium shell thicknesses and burnups. These parameters weren't explicitly specified in [3]. We point out again that the comparison addresses the flux shapes ratios, not their specific values. Another fine analysis is still needed to explain rigorously these differences.

6. Conclusions

The original result of the paper consists in an independent demonstration of the possibility to reduce the Coolant Void Reactivity using Hafnium as burnable absorber in the latest advanced CANDU fuel designs.

The secondary original contribution is the using of a methodology mostly based on non-commercial computer codes and an updated WIMS nuclear data library.

Last, we mention the developing of a Visual Basic procedure able to build input data files, run the 300 WIMS cases and draw the figures automatically in a few minutes.

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