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VOID EFFECT STUDIES CONCERNING ADVANCED CANDU FUEL PROJECTS

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A major drawback of the standard CANDU nuclear power reactor is the positive Coolant Void Reactivity (CVR). Several improved fuel designs known as Low Void Reactivity Fuel (LVRF) were proposed by AECL (Atomic Energy of Canada Limited) in the frame of the Advanced CANDU Reactor (ACR) project (CANDU, CANFLEX and ACR are registered trademarks of AECL). The paper presents the results of nuclear data sensitivity calculations on void effect with different CANDU fuel projects, containing both Natural Uranium (NU) and Slightly Enriched Uranium (SEU) with different enrichments. Twelve void fractions between 0 and 99% were considered for each fuel cell. The transport code DRAGON was used in this respect. The next step was to estimate the "sensitivity" induced by using different nuclear data i.e. two versions of the WIMS library emerged from the WLUP project sponsored by IAEA. The void reactivities for the advanced fuel projects are smaller than those calculated for standard CANDU and they are negative, as expected. Using the two versions of the WIMS library (based both on ENDF/B-VI and ENDF/B-VII) lead to less significant differences.

Keywords: ACR, CANFLEX, Coolant Void Reactivity, DRAGON, WLUP.

1. Introduction

Several improved fuel projects known as Low Void Reactivity Fuel (LVRF) were proposed by AECL in the frame of the Advanced CANDU Reactor (ACR) project. Some other projects are also considered in this paper that were previously taken into account in the frame of the studies dedicated to increasing the discharge burnup for CANDU reactors. The seven studied CANDU fuel projects are described in [1] and [2] and presented in Table 1.

The innovative concept of ACR-700 (studied project #1) improved both the fuel project and the reactor core design, by reducing the lattice pitch and the number of channels and also by using light water as coolant ([1]).

The main feature of the "low void reactivity" fuel projects #2 and #3 is the special combination between the bundle geometry and the different U235 enrichment across the fuel element rings, intended to provide a negative coolant void reactivity.

Early studies dedicated to burnup increasing used either the Natural Uranium (NU) or the Slightly Enriched Uranium (SEU) in the 37- or 43-element

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fuel bundles, keeping the same U235 enrichment in all fuel elements (projects #5, #6 and #7). Just like the standard CANDU fuel (project #4), these fuel projects were intended to be used in existing CANDU-600 reactors.

Table 1

Considered CANDU Fuel Projects

#	Fuel Project Name	Reactor Type	Fuel Geometry
1	ACR	ACR (700 MWe)	CANFLEX
2	CANFLEX-LVRF	CANDU (600 MWe)	CANFLEX
3	CANDU-LVRF		CANDU
4	CANDU		CANDU
5	CANFLEX-SEU		CANFLEX
6	CANDU-SEU		CANDU
7	CANFLEX-NU		CANFLEX

Basically, each fuel bundle has four Fuel Regions (FRs) described in Table 2, where

FR1: the central fuel element;
FR2: the inner ring (6 elements in CANDU geometry or 7 in CANFLEX);
FR3: the median ring (12 elements in CANDU geometry or 14 in CANFLEX);
FR4: the outer ring (18 elements in CANDU geometry or 21 in CANFLEX).

Table 2

Fuel Cell Data

#	Nr. of elem. region	Fuel Region	Fuel Temp. (K)	Dy (%)	U235 (%)	Fuel Density (g/cm^3)	Sheath Temp. (K)	Coolant Temp. (K)	Coolant D_2O Purity (%)	Mod. Temp. (K)	Mod. D_2O Purity (%)
1	1	FR1	1173.15	4.6	0.71	10.459	603.15	573.15	0	353.15	99.75
	7	FR2	1173.15	0	2	10.459	603.15	573.15	0	353.15	99.75
	14	FR3	1173.15	0	2	10.459	603.15	573.15	0	353.15	99.75
	21	FR4	1173.15	0	2	10.459	603.15	573.15	0	353.15	99.75
2	1	FR1	903.15	8.8	0.71	10.459	563.15	539.15	99.75	343.15	99.75
	7	FR2	903.15	1.9	0.71	10.459	563.15	539.15	99.75	343.15	99.75
	14	FR3	903.15	0	2.7	10.459	563.15	539.15	99.75	343.15	99.75
	21	FR4	903.15	0	2.1	10.459	563.15	539.15	99.75	343.15	99.75
3	1	FR1	903.15	10	0.71	10.459	563.15	539.15	99.75	343.15	99.75
	6	FR2	903.15	2	0.71	10.459	563.15	539.15	99.75	343.15	99.75
	12	FR3	903.15	0	1.92	10.459	563.15	539.15	99.75	343.15	99.75
	18	FR4	903.15	0	1.35	10.459	563.15	539.15	99.75	343.15	99.75
4	1	FR1	903.15	0	0.71	10.459	563.15	539.15	99.75	343.15	99.75
	6	FR2	903.15	0	0.71	10.459	563.15	539.15	99.75	343.15	99.75

	12	FR3	903.15	0	0.71	10.459	563.15	539.15	99.75	343.15	99.75
	18	FR4	903.15	0	0.71	10.459	563.15	539.15	99.75	343.15	99.75
5	1	FR1	903.15	0	0.96	10.459	563.15	539.15	99.75	343.15	99.75
	7	FR2	903.15	0	0.96	10.459	563.15	539.15	99.75	343.15	99.75
	14	FR3	903.15	0	0.96	10.459	563.15	539.15	99.75	343.15	99.75
	21	FR4	903.15	0	0.96	10.459	563.15	539.15	99.75	343.15	99.75
6	1	FR1	903.15	0	0.96	10.459	563.15	539.15	99.75	343.15	99.75
	6	FR2	903.15	0	0.96	10.459	563.15	539.15	99.75	343.15	99.75
	12	FR3	903.15	0	0.96	10.459	563.15	539.15	99.75	343.15	99.75
	18	FR4	903.15	0	0.96	10.459	563.15	539.15	99.75	343.15	99.75
7	1	FR1	903.15	0	0.71	10.459	563.15	539.15	99.75	343.15	99.75
	7	FR2	903.15	0	0.71	10.459	563.15	539.15	99.75	343.15	99.75
	14	FR3	903.15	0	0.71	10.459	563.15	539.15	99.75	343.15	99.75
	21	FR4	903.15	0	0.71	10.459	563.15	539.15	99.75	343.15	99.75

The fuel elements contain Uranium dioxide pellets with different U235 enrichments and they may also contain Dysprosium as a burnable "poison". For the CANDU geometry, all fuel elements are identical, while for CANFLEX the 8 (i.e. 1+7) inmost elements are thicker than the other 35 (i.e. 14+21) ones.

2. Reactor Operating Conditions

The reactor operating conditions considered in the simulations are usually known as "Hot Operating Conditions" (HOC) and they represent an equilibrium CANDU reactor core (full-power design parameters); for ACR, the expected design values ([1]) were used. The cell calculations were performed using the DRAGON code [3] that solves the neutron transport equation using the first collision probability method. The cell data are presented in Table 2.

Remember that for ACR the coolant only consists of light water (and therefore the coolant D_2O purity is 0).

3. Void Effect Studies

It is worthy to remind that the CANDU (and also ACR) fuel channels are horizontal and a loss of coolant accident (LOCA) usually leads to lowering the liquid level in the channel. Just to make things simple, the loss of coolant is simulated by reducing the homogenous coolant density:

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

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

The void reactivity (VR) is then defined as the difference reactivity between the normally cooled fuel cell (reference cell) and the cell from which some coolant was lost ("voided" cell):

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

where k_{inf}^{ref} and k_{inf}^{void} are the reference and "voided" cell neutron multiplication factors. The considered void fractions were: 0, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90 and 99%.

An original procedure was written in Visual Basic for Applications (VBA[2]) in order to prepare the input data, run DRAGON and make the graphs. For the first set of analyses, an ENDF/B-VI based nuclear data library was used.

The void reactivity was represented in Fig. 1, as a function of the void fraction, for all considered fuel projects. We also represented in Fig. 2 the void reactivity derivative with respect to the void fraction, referred as Coefficients of Void Reactivity (CVR) defined for each considered void fraction between 10% and 99% as:

$$CVR_i\,(mk\,/\,\%) = \Delta\rho^{void} / \Delta f = (\rho_i^{void} - \rho_{i-1}^{void}) / (f_i - f_{i-1}) \qquad (3)$$

where ρ_i^{void} is the void reactivity corresponding to the void fraction f_i, i = 1 to 12.

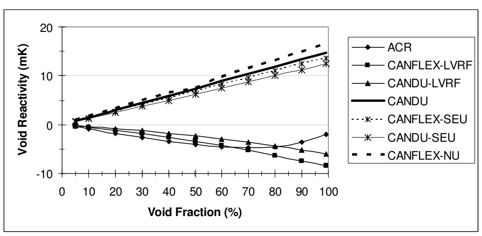

Fig. 1. Void Reactivity evolution with Void Fraction (ENDF/B-VI Nuclear Data).

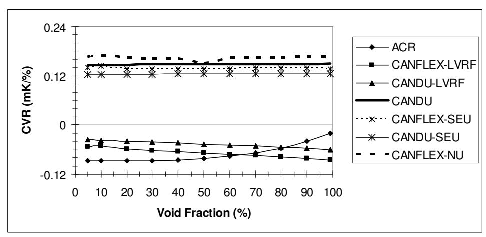

Fig. 2. CVR evolution with Void Fraction (ENDF/B-VI Nuclear Data).

For the standard fuel types (both CANDU and CANFLEX), the void reactivity effect is positive and it increases linearly with the void fraction. Their representative curves are close, though the fuel projects are quite different.

Since for ACR the Coolant Void Reactivity is a combined effect of losing H_2O absorption (positive) and losing D_2O moderation (negative), in order to make it more negative, the loss of moderation should be greater than the loss of neutron absorption. This can be achieved by reducing the lattice pitch (and consequently

[2] VBA is a registered trademark of Microsoft Corporation

the moderator volume), but slightly increasing the absorption rate by using additional absorbers. If those were added to the coolant, they would be lost during a LOCA, so the neutron absorbers should be added to the fuel element itself.

This is the reason for considering the ACR-700 project as "inherently safe": the elementary cell is "under-moderated" using H_2O instead of D_2O, the lattice pitch is reduced from 28.575 to 22 cm and the central fuel element contains some neutron absorber (Dysprosium) in order to maintain the absorption high even during LOCA. The void reactivity for this fuel type (the curve with black diamond marks in Fig. 1) is negative and it decreases with the void fraction, from -0.88 mk (corresponding to a void fraction f=10%) to -4.6 mk (for f=60%) and then slightly increases to -2 mk for the highly unlikely f=99%.

The void reactivity for CANDU-LVRF (represented by black triangle marks in Fig. 1 has the same behaviour as the ACR one, but it keeps on decreasing to -6 mk. Though the CANDU bundle geometry was kept, greater amounts of Dysprosium were added in the central 7 elements.

The other LVRF project, CANFLEX-LVRF, is the one having the best CVR: the void reactivity decreases to -8 mk when draining the cell.

The same calculations were performed using the "new" nuclear data provided by the IAEA sponsored WIMS Library Update Project (WLUP), based on the newly developed ENDF/B-VII.

Since no significant effect was observed when changing the nuclear data source (excepting the void reactivity at extreme void fractions), we only represented (in Figures 3 to 9) the void reactivity behavior for each considered fuel project, together with the relative difference induced by changing the nuclear data source:

$$eps\ \ (\%) = \frac{\rho_i^{void}(6) - \rho_i^{void}(7)}{\rho_i^{void}(6)} \cdot 100 \tag{4}$$

where $\rho_i^{void}(N)$ is the void reactivity corresponding to the void fraction f_i, i = 1 to 12 , estimated using ENDF/B-$\boldsymbol{N}$ data.

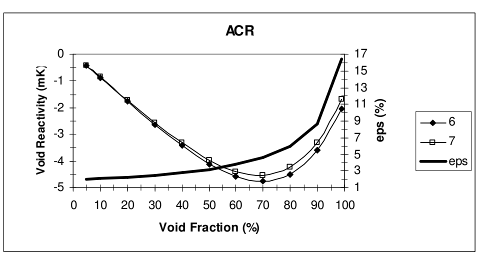

Fig. 3. Nuclear Data Source Effect on ACR Cell Void Effect.

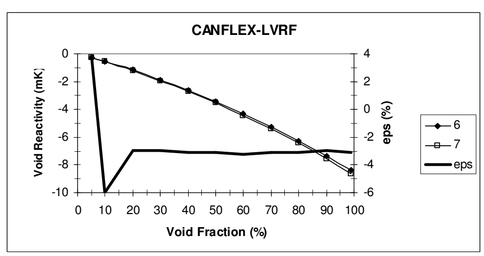

Fig. 4. Nuclear Data Source Effect on CANFLEX-LVRF Cell Void Effect.

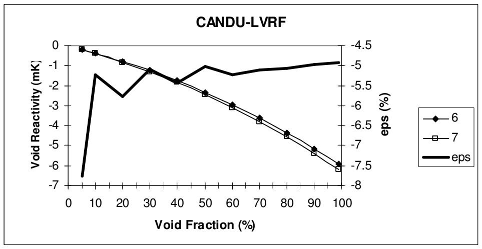

Fig. 5. Nuclear Data Source Effect on CANDU-LVRFCell Void Effect.

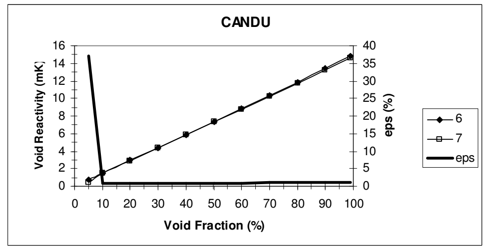

Fig. 6. Nuclear Data Source Effect on CANDU Cell Void Effect.

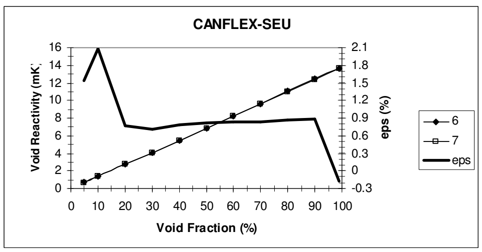

Fig. 7. Nuclear Data Source Effect on CANFLEX-SEU Cell Void Effect.

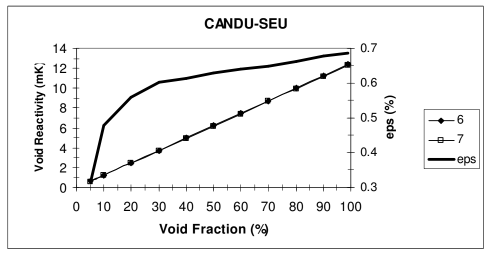

Fig. 8. Nuclear Data Source Effect on CANDU-SEU Cell Void Effect.

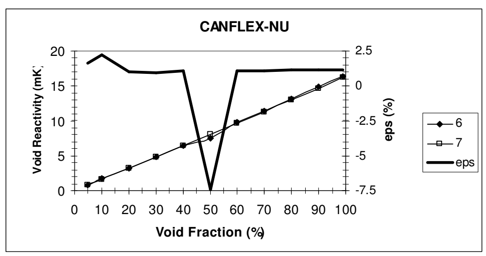

Fig. 9. Nuclear Data Source Effect on CANFLEX-NU Cell Void Effect.

The radial neutron flux distribution in the cell was also represented for all considered fuel projects, both for the normally cooled cells and for the "voided" ones. Remember that the ACR lattice pitch is 22 cm, while the CANDU one is 28.575 cm.

Figures 10 and 11 show the thermal flux distribution in the cell for each fuel project. We must remark the high thermal flux in the central fuel element for the bundles containing only NU or SEU, that usually leads to its overheating. The advanced projects have also a better behavior in this respect, since the thermal flux in the central fuel element is at least 10 times less for ACR, CANFLEX-LVRF and CANDU-LVRF than for CANDU, CANFLEX-NU, CANDU-SEU and CANFLEX-SEU. Table 3 shows the legend for Figures 10 and 11:

Table 3

Legend for Figures 10 and 11

ACR	CANFLEX-LVRF	CANDU-LVRF	CANDU	CANFLEX-SEU	CANDU-SEU	CANFLEX-NU
--◆--	--■--	--▲--	———	---✳---	- - -✳- - -	— — — —

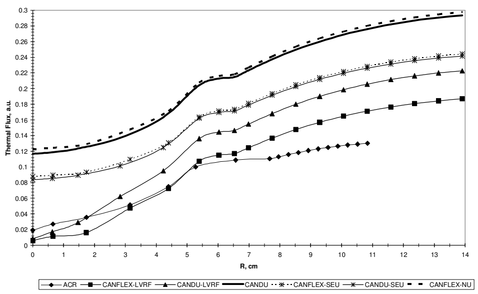

Fig. 10. Thermal Flux Distributions for "Cooled" Cells (f = 0%).

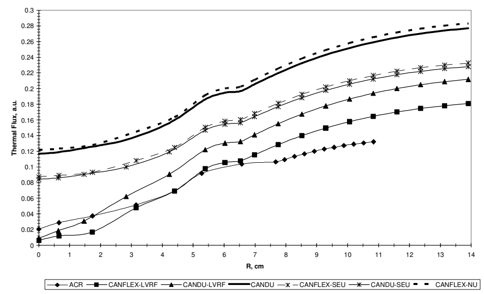

Fig. 11. Thermal Flux Distributions for "Voided" Cells (f = 99%).

4. Conclusions

The ACR-700 innovative project may be considered "inherently safe", at least from the CVR point of vue, since the void reactivity for this fuel type is negative and it decreases with the void fraction, from -0.88 mk (corresponding to a void fraction f=10%) to -4.6 mk (for f=60%) and then slightly increases to -2 mk for the highly unlikely f=99%. Also, both CANDU and CANFLEX low void reactivity fuel bundles show negative CVRs, the void reactivity decreasing to -8 mk for the drained cell. For the standard fuel types (both CANDU and CANFLEX), the void reactivity effect is positive and it increases linearly with the void fraction. Their representative curves are close, though the fuel projects are quite different. No significant effect was observed when changing the nuclear data source (using the "new" nuclear data based on the newly developed ENDF/B-VII instead of the "old" ones based on ENDF/B-VI), excepting the void reactivity at extreme (and highly unlikely) void fractions.

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