Coolant Void Reactivity Analysis of CANDU Lattice

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1. Introduction

The Advanced CANDU Reactor-700 (ACR-700) was proposed by Atomic Energy of Canada Limited (AECL) as a next generation CANDU reactor [1]. By reducing the fuel pitch, changing the coolant material, and changing from the 37-element CANDU-6 fuel bundle to the 43-element CANFLEX fuel bundle, ACR-700 has a negative coolant void reactivity (CVR), unlike the previous CANDU lattice [2]. Models of CANDU-6 and ACR-700 fuel lattices were constructed for a single bundle and 2 by 2 checkerboard to understand the physics related to CVR.

Also, a familiar four factor formula was used to predict the specific contributions to reactivity change in order to achieve an understanding of the physics issues related to the CVR [3-5]. At the same time, because the situation of coolant voiding should bring about a change of neutron behavior, the spectral changes and neutron current were also analyzed. The models of the CANDU-6 and ACR-700 fuel lattices were constructed using the Monte Carlo code MCNP6 using the ENDF/B-VII.0 continuous energy cross section library based on the specification from AECL [6]. The CANDU fuel lattice was searched through sensitivity studies of each design parameter such as fuel enrichment, fuel pitch, and types of burnable absorber for obtaining better behavior in terms of CVR.

2. CVR Analysis of Single Fuel Bundle Voiding

CVR analysis was performed on 2-dimensional CANDU-6 and ACR-700 fuel lattices with the reflective boundary condition. The four factors were calculated from the fission and absorption reaction rates from the F4 tally capability in MCNP6. The simulation was carried out for 0% voiding and instantaneous 100% voiding of the coolant.

2.1 Normalized Neutron Spectra

Figure 1 shows the normalized neutron spectra of a CANDU-6 and ACR-700 fuel lattices at 0% and instantaneous 100% coolant voiding. Because most neutron are moderated within the sufficiently big moderator region of the calandria of the CANDU-6 reactor, the coolant voiding doesn't affect the amount of overall neutron moderation.

However, the up-scattering effect, which caused by the collisions of neutrons from the low temperature moderator region with the high temperature coolant molecules, decreases because of the reduction of the coolant density, and it results in a thermal spectrum shift to a lower energy region. Also, the loss of coolant causes the reduction of high energy neutron moderation and results in a hardening of the high energy spectrum. Therefore, the coolant voiding of a CANDU-6 lattice results in energy shifts for both the thermal and fast parts of the neutron energy spectrum. Shifting of the energy spectrum to a lower energy range which has a larger fission cross section of ^{235}U causes an increase of thermal fission. At the same to, shifting the fast spectrum to a harder energy range also causes an increase of fast fission of ^{238}U, so, the reactivity effect of voiding is positive in the CANDU-6 lattice.

In contrast to the spectral change of the CANDU-6 fuel lattice, there is a significant reduction of thermal flux on coolant voiding. The reduction of fuel lattice pitch and increment of the slowing-down power of light water compared to heavy water lead to more neutron moderations in the coolant of the ACR-700 than in the CANDU-6 fuel lattice. Therefore, the reduction of thermal neutrons results in a negative reactivity change in the case of coolant voiding.

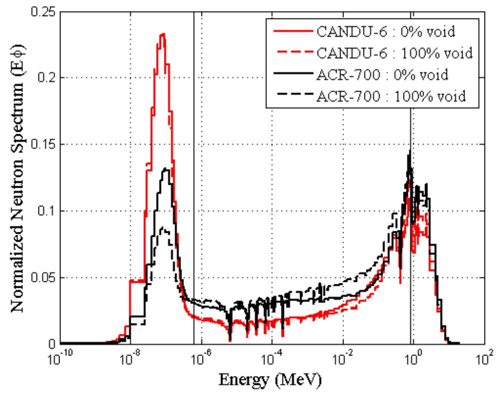

Fig. 1. Normalized neutron spectra at 0% and 100% coolant voiding.

2.2 Four Factor Analysis

In this study, the three group energy structure (thermal, epithermal, and fast) was used. In order to clearly understand the physics of coolant voiding, the resonance escape probability is separated into epithermal and fast groups. The fast and epithermal resonance escape probability are escape from loss terms for the fast and epithermal groups, respectively. The four factors include the fast fission factor (ε), the resonance escape probability (p_E , p_F), the thermal utilization factor (f), and the reproduction factor (η_T). Table I summarizes the specific contribution of each parameter to the total reactivity change for the two fuel lattices.

The fast fission factor provides a positive reactivity contribution in the CANDU-6 lattice because of the hardened spectrum in the fission spectrum energy range. Likewise, it provides a positive reactivity contribution in the ACR-700 lattice. Because the reduction of moderator to fuel volume ratio leads to insufficient neutron moderation on coolant voiding, the reactivity contribution is much larger in magnitude than that in the CANDU-6 lattice. The epithermal resonance escape probability provides a positive reactivity contribution in the CANDU-6 lattice because of the redistribution of epithermal neutrons to the moderator region and thereby the reduction of the ^{238}U resonance absorption. However, the impact to epithermal resonance escape probability is large and negative because of the reduced moderation upon coolant voiding in the ACR-700 lattice. The fast resonance escape probability provides a negative contribution in the CANDU-6 because the fast neutron shifts to the higher energy level and the down-scattering ability is decreased. Similar to the CANDU-6 lattice, the fast resonance escape probability provides a negative reactivity contribution. The reduction of thermal neutron absorption by the coolant provides a positive effect to the thermal utilization factor, and the shift in the thermal spectrum to a range with a larger thermal fission cross section and smaller macroscopic capture cross section makes the reproduction factor provide a positive reactivity contribution in the CANDU-6. The thermal utilization factor provides a much larger positive contribution in the ACR-700 lattice than in CANDU-6 because the voiding of light water decreases the neutron absorption in the coolant more than that of heavy water. The reduction of thermal flux and thermal fission makes the reproduction factor become a negative reactivity contribution in the ACR-700 lattice.

3. CVR Analysis of Checkerboard Voiding

It can be inferred that the ACR-700 lattice can be safer than the CANDU-6 lattice in accident situations like an instantaneous coolant boiling because the ACR-700 lattice has a negative coolant void reactivity. However, the accident situation of a single pump failure can cause the ACR-700 checkerboard voiding instead of the full voiding because the coolant pumping system of a CANDU reactor operates like a checkerboard.

Table I: Void reactivity components of CANDU-6 and ACR-700 lattices on single fuel bundle voiding

	Factor	0% void	100% void	Reactivity effect [mk]	
CANDU-6	ε	1.084	1.090	$\Delta\rho_{\varepsilon}$	4
	p_E	0.855	0.865	$\Delta\rho_{p_E}$	9
	p_F	0.976	0.973	$\Delta\rho_{p_F}$	-2
	f	0.950	0.953	$\Delta\rho_{f}$	3
	η_T	1.321	1.322	$\Delta\rho_{\eta_T}$	1
	k_∞	1.136	1.155	CVR	15
ACR-700	ε	1.143	1.201	$\Delta\rho_{\varepsilon}$	37
	p_E	0.750	0.686	$\Delta\rho_{p_E}$	-68
	p_F	0.975	0.971	$\Delta\rho_{p_F}$	-4
	f	0.913	0.960	$\Delta\rho_{f}$	39
	η_T	1.651	1.626	$\Delta\rho_{\eta_T}$	-12
	k_∞	1.260	1.248	CVR	-8

3.1 Three-group Neutron Current

Table II presents the three energy group surface currents normalized per a fission source neutron of the 0% void ACR-700 bundle at normal and checkerboard coolant voiding conditions. The fast neutrons are moderated insufficiently in the coolant voiding bundle due to smaller amount of moderator of the ACR-700 lattice than that of CANDU-6 lattice. This results in an increase of the amount of fast and epithermal neutrons moving from the 100% void to no-void channels, and also a reduction of the amount of thermal neutron current leaving the voided channel. It increases the fast fission of ^{238}U in the voided channel and, at the same time, the thermal fission at the 100% void bundle occurs more due to the increased thermal neutrons from the 0% void bundle to the 100% void bundle. Therefore, the checkerboard coolant voiding in the ACR-700 fuel lattice results in more fission reactions, and it leads to a positive reactivity effect.

Table II: Surface current from no-void channel of ACR-700 lattice upon normal and checkerboard voiding

	Normal condition [#/cm^2]	Checkerboard voiding [#/cm^2]		
		Incoming	Outgoing	Net*
Fast	4.55E-02	5.31E-02	4.85E-02	-4.59E-03
Epi-thermal	4.16E-01	5.07E-01	4.92E-01	-1.44E-02
Thermal	4.88E-01	4.54E-01	4.69E-01	1.54E-02

* positive sign means a neutron flow from no-void to voided channel, and negative sign means a neutron flow from voided to no-void channel

Figure 2 illustrates the neutron behaviors when checkerboard coolant voiding occurs. The fast and epithermal group neutrons in the 100% voided bundle move to the no-void bundle, being moderated to thermal group in that channel, then the thermal neutrons come back to the voided channel. This new path for neutron moderations in checkerboard voiding is the main reason for the positive CVR, whereas it is negative in full voiding.

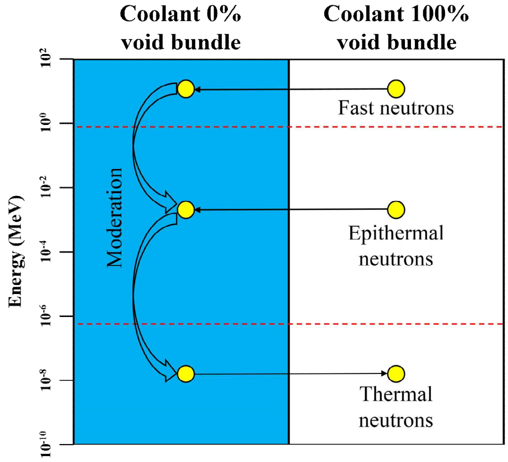

Fig. 2. Neutron behaviors upon checkerboard voiding.

3.3 Four Factor Analysis

Table III presents the void reactivity components of an ACR-700 fuel lattice upon checkerboard coolant voiding. The epithermal resonance escape probability and the reproduction factor take a significant role to make a positive CVR on checkerboard coolant voiding in contrast to the single bundle voiding. Existence of the new path for neutron moderation makes the increment of epithermal and fast fluxes to be smaller than that on single bundle coolant voiding. By reducing the resonance absorption as the spectrum shifts to a range of smaller absorption cross section, the epithermal resonance escape probability causes less contribution to reactivity on checkerboard voiding than on single bundle voiding. The reproduction factor also provides less contribution to reactivity on checkerboard voiding than single bundle voiding because the decrement of the thermal fission reaction rate on checkerboard voiding is smaller than on single bundle voiding. Unlike the epithermal resonance escape probability and the reproduction factor, the fast fission factor, the fast resonance escape probability, and the thermal utilization factor make a more negative reactivity contribution on checkerboard coolant voiding than the single bundle full voiding. Therefore, checkerboard coolant voiding leads to a positive reactivity effect in contrast to single bundle coolant voiding.

Table III: Void reactivity components of ACR-700 lattice upon checkerboard voiding

Factor	Checkerboard voiding			Reactivity effect [mk]	
	0% void	100% void	Total		
ε	1.159	1.170	1.165	$\Delta\rho_{\varepsilon}$	14
p_E	0.708	0.740	0.724	$\Delta\rho_{p_E}$	-27
p_F	0.974	0.967	0.970	$\Delta\rho_{p_F}$	-5
f	0.915	0.960	0.937	$\Delta\rho_{f}$	20
η_T	1.645	1.654	1.649	$\Delta\rho_{\eta_T}$	-1
k_{∞}	1.204	1.327	1.262	CVR	1.52

4. Sensitivity Study of CANDU Lattice

As stated in previous sections, while the ACR-700 fuel lattice has a negative CVR in the case of single bundle coolant voiding, it has a positive CVR upon checkerboard voiding. In order to make the CVR negative even on checkerboard voiding, a sensitivity study was performed for various design parameters.

4.1 Fuel Enrichment and Moderator to Fuel Volume Ratio

Figure 3 shows the multiplication factor of CANDU-6 and ACR-700 lattice as function of the moderator to fuel volume ratio at hot zero power conditions. Yellow points represent the current CANDU-6 and ACR-700 fuel lattices. The black tangential lines on those yellow points represent the rate of reactivity changes due to the variation of the moderator to fuel volume ratio. It is apparent that the ACR-700 lattice is further under-moderated region than CANDU-6 from the figure which makes the ACR-700 CVR negative in the full voiding case.

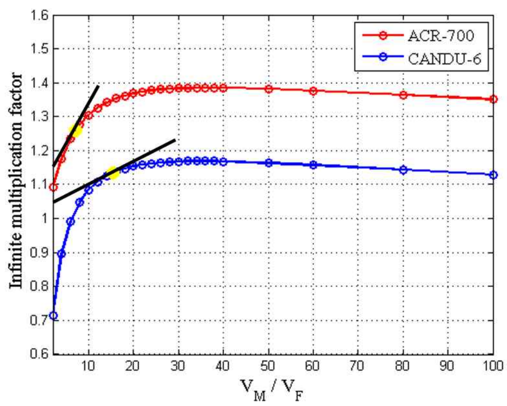

Fig. 3. Multiplication factor as function of the moderator to fuel volume ratio.

Figure 4 shows the multiplication factor vs. moderator to fuel volume ratio behaviors of the ACR-700 fuel lattices with 0.72, 2.10, and 4.50 wt. % ^{235}U enriched UO_2 fuels. Yellow points in the figure represent the current lattice pitch cases with 22.0 cm. It should be noted that the slopes of tangential lines at those yellow points are bigger for higher enrichment. In other words, higher enrichment of fuel makes the lattice more under-moderated at the same moderator to fuel volume ratio.

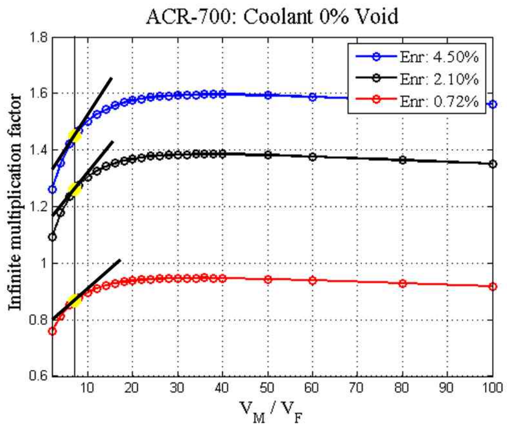

Fig. 4. Multiplication factor behavior for various enrichment of ^{235}U.

Figure 5 shows the CVR vs. moderator to fuel volume ratio behaviors of single bundle coolant voiding and checkerboard voiding for various ^{235}U enrichments. Yellow points represent the current design ACR-700 lattice. With current geometries, fuel lattices with 4.50 wt. % enriched fuel have negative CVRs on both single bundle and checkerboard voiding. It is apparent that either the increase of enrichment or the decrease of moderator to fuel volume ratio can reduce the CVR. It is because higher enrichment of fuel makes the fuel lattices more under-moderated.

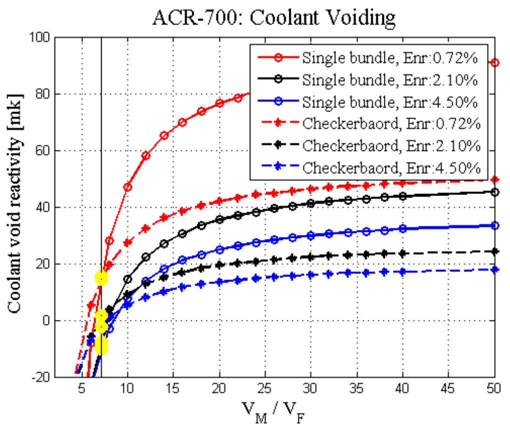

Fig. 5. CVR for variations of ^{235}U enrichment upon single bundle and checkerboard coolant voiding.

4.2 Burnable Neutron Absorber

The ACR-700 lattice has a burnable neutron absorber (BA) in the center fuel rod to help the CVR become negative. A sensitivity study of the burnable absorber was carried out for different burnable absorber materials which have been used in PWRs. Gadolinia (Gd_2O_3), erbia (Er_2O_3), and boron carbide (B_4C) is used for this study.

Figure 6 shows the multiplication factor behaviors of fuel bundles with four burnable absorber materials. Yellow points in the figure indicate the points with the weight percent of each burnable absorber which can make the initial excess reactivity the same as that using 7.5 wt. % dysprosium. Note that boron carbide can achieve the same initial excess reactivity with the smallest weight percent of burnable absorber.

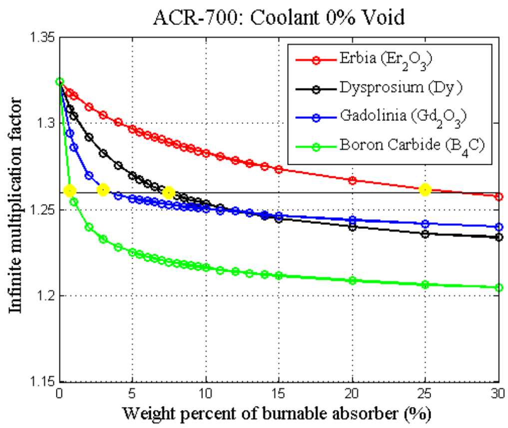

Fig. 6. Multiplication factor using various types of BA.

Figure 7 shows the CVR behaviors depending on burnable absorber materials on single fuel bundle and checkerboard coolant voiding. When the weight percent of burnable absorbers are chosen such that the initial reactivity are the same as the one using 7.5 wt. % dysprosium, the fuel bundles with either gadolinia, erbia, or boron carbide have negative CVRs on single bundle coolant voiding but positive on checkerboard coolant voiding. It was found that the ACR-700 fuel bundle with boron carbide as burnable absorber instead of dysprosium has slightly negative CVR even on checkerboard voiding.

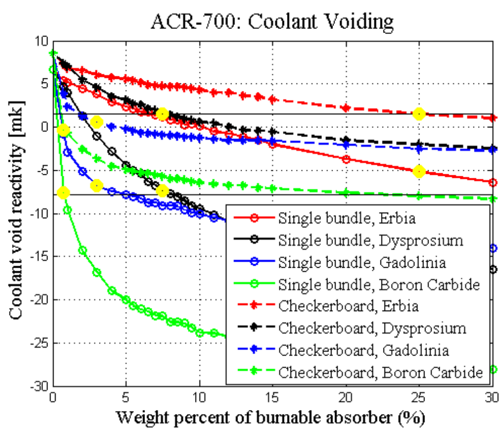

Fig. 7. CVR behaviors depending on BA materials upon single bundle and checkerboard voiding.

5. Conclusions

The CVR analyses of CANDU-6 and ACR-700 fuel lattices were performed on single bundle coolant voiding and checkerboard voiding. The underlying physics of CVR was explained by analyzing the spectral shifts and four factor reactivity contributions. Because the ACR-700 lattice is under-moderated, the ACR-700 lattice has negative CVR in contrast to the CANDU-6 lattice upon single bundle coolant voiding. Unlike the single channel coolant voiding, the ACR-700 bundle has a positive reactivity change upon 2x2 checkerboard coolant voiding. Because of the new path for neutron moderation, the neutrons from the voided channel move to the no-void channel where they lose energy and come back to the voided channel as thermal neutrons. This phenomenon causes the positive CVR when checkerboard voiding occurs. The sensitivity study revealed the effects of the moderator to fuel volume ratio, fuel enrichment, and burnable absorber on the CVR. A fuel bundle with low moderator to fuel volume ratio and high fuel enrichment can help achieve negative CVR. Additionally, it was found that boron carbide, instead of dysprosium, can make the fuel bundle have a negative CVR even on checkerboard coolant voiding.

Acknowledgements

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