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ERBIA-LOADED CANDU FUEL FOR MINIMIZATION OF THE COOLAND VOID REACTIVITY

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ABSTRACT –To improve the inherent safety of the CANDU6 reactor, the coolant void reactivity (CVR) should be minimized. This work is concerned with minimization of the coolant void reactivity of a CANDU6 reactor loaded with natural U CANFLEX fuel. In this work, a burnable absorber of Er_2O_3 (erbia) is used to minimize the CVR of CANDU6 reactor. Erbia is directly admixed with the UO_2 fuel as is utilized in the PWR applications. The allowable range of erbia loading in UO_2 pellet is reviewed in terms of the fuel thermal conductivity. The optimal loading of erbia is investigated through lattice-based analysis and its impacts of on the lattice characteristics are discussed. In particular, both the fuel Doppler effect and coolant void reactivity are evaluated for the lattice. For a more reliable analysis, a 3-D equilibrium core is determined by using the standard time-average methods for erbia-loaded CANDU6 cores by using an in-house code system. The core analysis is based on a hybrid two-step method in which the lattice analysis is performed by the Serpent Monte Carlo code and the 3-D core analysis is performed by a diffusion theory code named COREDAX. To compensate for the negative reactivity due to the erbia loading, some of the adjuster rods are removed to increase the fuel discharge burnup. Both partial and complete removal of the adjuster rods are considered in this study. For the derived equilibrium cores, the core performances are evaluated in terms of the fuel burnup, power profile. Also safety parameters including the CVR are evaluated for the equilibrium core condition. Safety parameters of the 3-D core are compared with those obtained with simple lattice-based analysis.

Introduction

A strictly positive Coolant Void Reactivity (CVR) has been a major safety concern of the CANDU (CANada Deuterium Uranium) reactor.As one of important safety parameters in nuclear reactor, the CVR is defined as the reactivity change by voiding all the coolant inside core. In general, light water reactors (LWRs), CVR is stronglynegative. However, CANDU reactor has clearly positive CVR value because of its uniquefuel bundle configurations. In CANDU reactor, moderator is separated from fuel and coolant by a pressure tube and the so-called calandria tube. A positive CVR indicates that positive reactivity will be inserted in case of the loss of coolant accident (LOCA), which will lead to sudden reactor power increase during accident,if there is no safety mechanism working properly. To achieve a high level of safety, the CANDU system is equipped with fast-acting secondary shutdown system, in addition to the conventional shutdown mechanism.

Power Coefficient of Reactivity (PCR) is also a very important safety parameter for the inherent safety of nuclear reactors. The PCR, which is defined as reactivity change per unit power change, is the combined effect of Fuel Temperature Coefficient (FTC) and Coolant Temperature Coefficient (CTC) as temperatures of both fuel and coolant change with power. For the inherent stability and safety of nuclear reactors, PCR is required to be negative.In the old CANDU designs, the FTC value was calculated to be clearly negative and its PCR for at 100% power equilibrium core was evaluated to be slightly negative. However, it was recently found that, with modern reactor physics code, PCR of the CANDU reactor can be very close to zero or even slightly positive [1-3]. For a more detailed analysis, Kim et al. evaluated burnup- and temperature-dependent safety parameters of the CANDU reactor by using high-fidelity Monte Carlo calculations with Doppler Broadening Rejection Correction (DBRC) scheme [4-6]. It was demonstrated that both its FTC and PCR were noticeably improved when thermal motion of the 238-U isotopes is accounted for. Motalab et al. later confirmed this conclusion with a high-fidelity 3-D whole-core Monte Carlo simulation [7].

There have been many attempts to enhance the safety parameters of the CANDU reactor. The CANduFLEXible (CANFLEX) fuel bundle has been developed as a CANDU advanced fuel to enhance fuel performance and operating margins [8, 9]. Also, there was a further improvement made for CANFLEX fuel which reduces CVR by inserting poison material in central pin, and it named as CANFLEX-LVRF (low void reactivity fuel) [10,11]. In a recent study, Rohet al.[2] introduced an Er (erbium) burnable absorber into the CANFLEX fuel in order to improve the FTC and make the PCR value negative for the operating conditions. In their work, a recovered U (RU) [12] has been used to achieve a fuel discharge burnup greater than that of the conventional natural U (NU). Ref. 2 showed that the FTC and CVR can be greatly improved by use of the Er burnable poison in CANDU. However, the neutronic methods used in Ref. 2 are rather standard and the thermal motion of 238-U was not accounted for. Also the study in Ref. 2 was based on lattice analyses.

In this study, we tried to improve the CVR and FTC of CANDU by utilizing an Er burnable poison in a unique way such that the fuel discharge burnup of the Er-loaded CANDU should be the same as in the standard one without any fuel enrichment.The CANFLEX fuel design is considereddue to its better thermal hydraulic performances than standard fuel design. In order to compensate for reactivity loss due to erbium loading, we removed some or all of adjuster rods from the core.

1. Analysis Methods

1.1 CANDU lattice calculation model

The 2-D lattice depletion calculation and preliminary evaluation of safety parameters were performed using the Monte Carlo Serpent2code [13] with ENDF/B-7.0 nuclear data. The general CANFLEX fuel lattice configuration was used [9, 14]. Serpent2 is a Monte Carlo code developed by VTT Technical Research Center of Finland, which uses continuous-energy cross-section data and is able to account for the thermal motion of any target atoms using the DBRC method. A detailed information shown in Table 1 is used for the lattice model.To represent a CANDU core operating at full power with a single lattice, the bundle-power-weighted average coolant temperature and ring-wise fuel temperature were determined [14], which are based on the whole core power and temperature distribution calculated by coupling of 3-D RFSP [15] and NUCIRC codes [16].

To evaluate the FTC by using the Monte Carlo method, the infinite multiplication factor was first calculated for eight fuel temperatures (600 K, 699 K, 801 K, 909 K, 961 K, 1010 K, 1072 K, and 1200 K), then results were used in fitting into an empirical formula [17].The CVR values at 100% power of the CANFLEX lattice were also calculated and compared. The CVR can be calculated at hot full power condition by changing coolant density from nominal value to the voided value (0.00118 g/cm^3) as follows:

$$\alpha_{void}(mk) = \left[\frac{1}{k_{\text{nominal}}} - \frac{1}{k_{\text{voided}}}\right] \times 1000. \quad (1)$$

Table 1. Calculation conditions of CANFLEX fuel lattice

Parameters	value
Number of fuel pins	43
Pins on each ring	1, 7, 14, 21
Fuel pin radius (mm)	6.35 (inner) / 5.35 (outer)
Fuel temperature (K)	
1st ring	871.45
2nd ring	889.21
3rd ring	834.17
4th ring	898.80
Average	875.57
Coolant temperature (K)	561.83
Cladding, Pressure tube temperature (K)	561.83
D_2O purity	
Coolant	99.1 wt%
Moderator	99.8 wt%
Specific power (W/gU)	33.7

1.2 CANDU time-average core model

For the whole core calculation of CANDU, the 3-D diffusion nodal code COREDAX-2 was used [18]. In original, the COREDAX-2 code and its Analytic Function Expansion Nodal (AFEN) method have been developed in KAIST, for the purpose of general light water reactor analysis. However, COREDAX-2 can also be used for the CANDU type reactor analysis if appropriate core modeling and nuclear cross section data are prepared.

1.2.1 CANDU core modeling for COREDAX-2

As previously mentioned, Monte Carlo lattice code Serpent2 was used to evaluate burnup-dependent 2-group homogenized cross section data using 2-D lattice model. However, 3-D supercell lattice analysis is mandatory to calculate the impact of “vertically inserted” reactivity devices. Serpent2 was used to evaluate supercell cross sections for all kinds of reactivity devices using detailed 3-D model. As a result, the standard CANDU incremental cross section was calculated from its definition [19]:

$$\Delta\Sigma_{T,x} = \Sigma_{T,x} - \Sigma_{A,x}, \quad (2)$$

where $\Delta\Sigma_{T,x}$ is an incremental cross section of reaction x, $\Sigma_{T,x}$ is a lattice cross section with reacitivity device of reaction x and $\Sigma_{A,x}$ is a lattice cross section without reacitivity device of reaction x.In the rectangular geometry of COREDAX-2, 26 * 26 * 14 nodes are needed to describe

3-D CANDU reactor. As shown in Figure 1, this modeling includes 380 fuel channels, 2 layers of radial reflectors, and 1 layers of axial reflector at top and bottom. It should be noted that top two and botton two channels have vault water (light water) as the outer layer of radial reflector. Considering high nertron absorption cross section of light water compared to heavy water, their impact on the core is not very small at all. Also, axial reflectors are homogenized including the complex on-power fuel reloading mechanism.

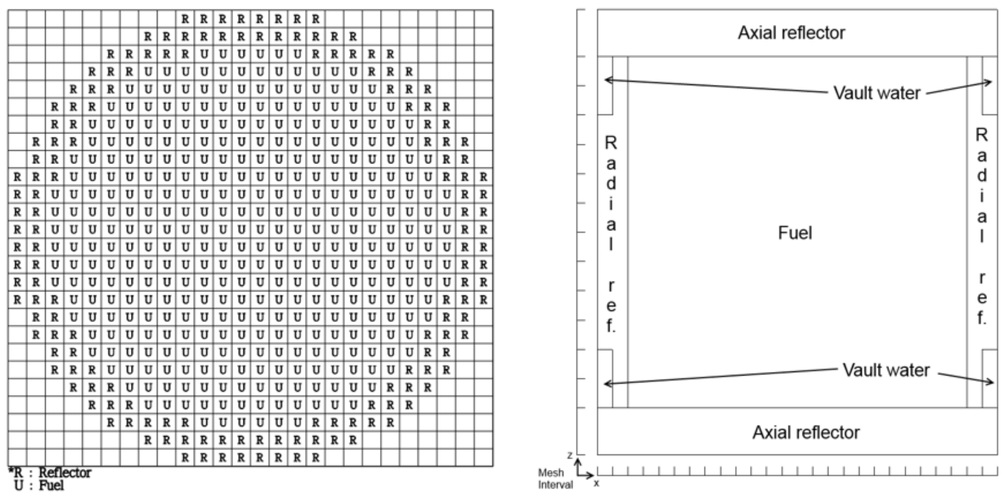

Figure 1. radial (left) and axial (right) configuratin of CANDU core modeling in COREDAX-2

<u>1.2.2 Time-average module</u>

Because fuel loading changes everyday in CANDU reactor, an “average” or “equilibrium”core model is recommanded for the reactor physics analysis. In the so-called “time-average” core for CANDU reactor, lattice cross sections are averaged over residence time of fuel bundles. In this study, a “time-average” module was developed for the COREDAX-2 code based on the standard method used in the RFSP-IST code and it is well described in Ref. 19. The resulting time-averaged lattice cross-section of reaction *i* at “channel number *j* and axial position *k* within that channel” is defined as follows [19]:

$$\Sigma_{i,jk}(t.av.) = \frac{1}{(\omega_{out,jk} - \omega_{in.jk})} \int_{\omega_{in.jk}}^{\omega_{out.jk}} \Sigma_i(\omega) d\omega, \tag{3}$$

where $\Sigma_i(\omega)$ is the irradiation-dependent cross section i,$\omega_{in,jk}$ and $\omega_{out,jk}$ are the incoming and outgoing values of irradiation at location *jk*.

The final solution of Eq. (3) is obtained as a result of iterative calculation between Eq. (3) and whole core diffusion analysis. The flux distribution from the COREDAX-2 code is used to calculate the incoming and outgoing irradiations in Eq. (3) and the lattice-wise time-average cross section is used in the COREDAX-2 code. COREDAX-2 and the time-average module are coupled using a Windows batch script. The calculational flow chart for the time-average core search is shown in Figure 2.

When evaluating the CVR using time-average core, following method was used. First, we performed general time-average iteration to get the reactivity of nominal condition in Eq. (3). Also, we saved $\omega_{in,jk}$ and $\omega_{out,jk}$ at nominal condition for every location. Then, time-average cross section of voided condition is calculated directly using Eq. (5), using voided cross section $\Sigma_{i,voided}(\omega)$ and nominal condition $\omega_{in,jk}$ and $\omega_{out,jk}$.

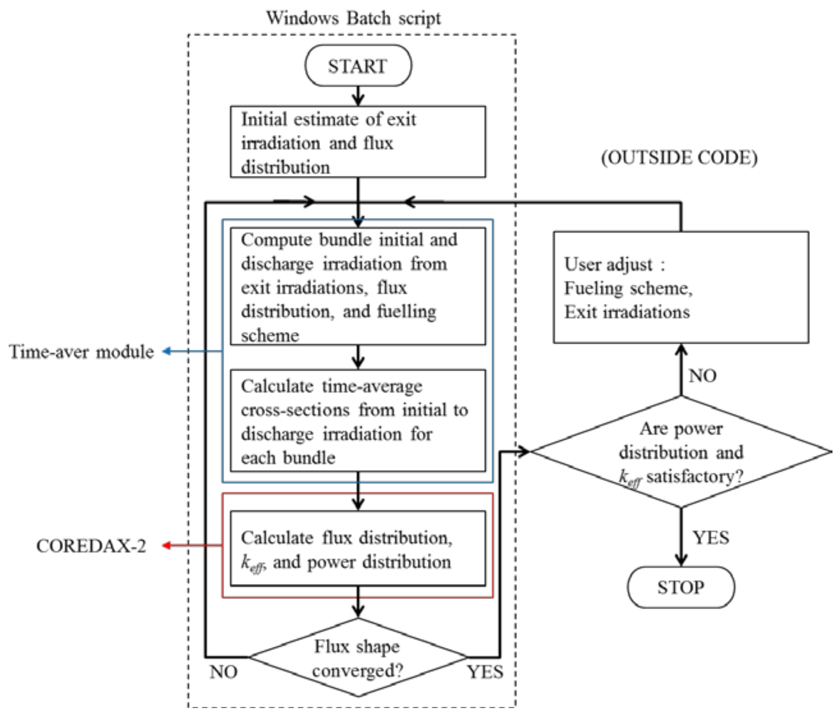

Figure 2. flow chart of time-average core search using COREDAX-2

2. Optimization of Erbia Loading in CANFLEX

In this study, the use of erbium burnable absorber in CANFLEX fuel is introduced to improve the safety parameters of the CANDU reactor. Roh et al.[2] have shown that an Er burnable poison mixed with fuel can improve both FTC and CTC of the CANDU6 reactor. There are 6 naturally occurring Er isotopes: Er-162 (0.14 a/o), Er-164 (1.61 a/o), Er-166 (33.61 a/o), Er-167 (22.93 a/o), Er-168 (26.78 a/o), Er-170 (14.93 a/o), and Er-167 is the only strong absorber. The capture cross-section of 167-Er is shown in Figure 3.

By homogeneous loading of burnable absorber in the central fuel element of CANFLEX fuel bundle, more negative FTC and less positive CTC can be obtained because a) Doppler effect of Er itself enhances neutron capture by Er at higher fuel temperature, and b) Er suppresses thermal neutrons in the central region in case of coolant voiding. In the previous study, Er_2O_3 was found to be the best option among various well-known burnable poisons in terms of PCR improvement and discharge burnup [2,3]. 167-Er has a large capture resonance at thermal energy region (~0.5 eV), which is expected to be effective in the well-moderated CANDU6 environment. Ref. 2 also demonstrated that an Er_2O_3 burnable poison should be loaded into the central fuel element for maximal benefits of the Er burnable absorber. Figure 4 shows the configuration of CANFLEX fuel bundle with the Er burnable absorber. In this work, it is assumed that Er_2O_3 is simply homogeneously admixed with the UO_2 fuel.

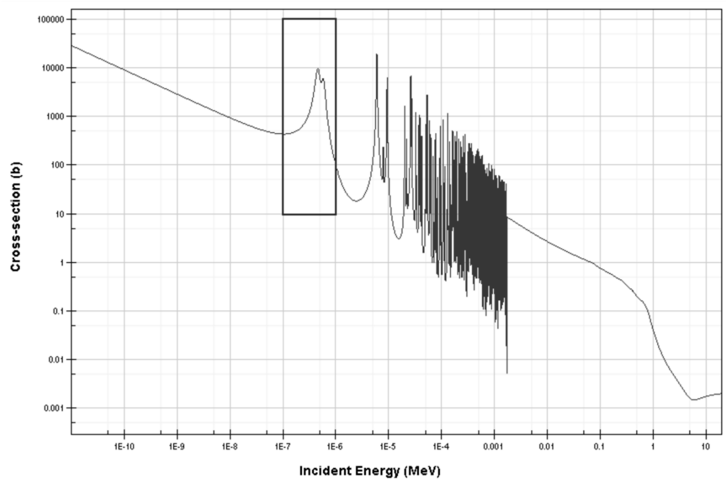

Figure 3. Capture cross-section of 167Er (ENDF-B/VII.0)

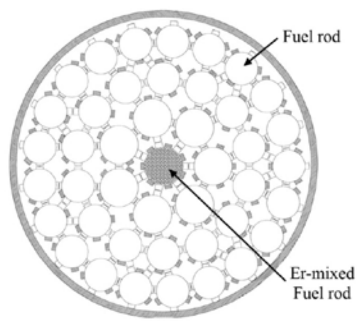

Figure 4. Configuration of Er-loaded CANFLEX fuel bundle

2.1 Reactivity compensation by removing adjuster rods

However, it is inevitable that the loading of Er burnable absorber should reduce the lattice reactivity and the achievable discharge burnup of the natural U (NU) fuel would be lower than the typical value of 7,200 GWd/tU. In order to deal with the problem, a recovered U (RU) was used to increase the fuel burnup in Ref. 2. However, the RU option requires a long fuel development period for actual realization of the Er-loaded CANFLEX fuel.

Instead of increasing the initial U-235 enrichment for the fresh fuel, a unique approach is adopted in this work to maintain the current discharge burnup even with the Er-loaded CANFLEX-NU fuel. In this study, removal of part or all of the adjuster (ADJ) rods from the CANDU6 reactor is proposed to compensate for the reactivity reduction by the Er burnable absorber. There are 21 ADJ rods in the CANDU6 reactor and they are basically stainless steel neutron absorber which are fully inserted during the normal operation of CANDU6 [20].

The adjuster rods are used to adjust the core power distribution. They can also be used to compensate for a large negative reactivity resulting from Xe buildup during power transient such as rapid power reduction. Also, withdrawing ADJ rods can provide positive reactivity when the refueling machine is not available for some finite time. Another important role of ADJ rods is that ADJ rods should be fully inserted for a quick restart of reactor after a sudden trip [20, 21].

In the current CANDU6 reactor, the total reactivity worth of the adjuster rods is about 16 mk and this positive reactivity is required to compensate for a large negative reactivity due to xenon buildup ~30 minutes after a reactor trip at full power equilibrium state. However, this use of adjuster rods has become not practical nowadays since nuclear reactors cannot be quickly restarted after a sudden reactor trip due to more stringent regulations. And in some Canadian CANDU reactors, some or all of the ADJ rods are already removed from the core to maximize the fuel utilization [21].

Taking into account the current experiences with the ADJ rods, two options of adjuster rod removal are considered in this study. The first option is removing only about 4 adjuster rods to increase the reactivity by ~5.44 mk. The remaining ADJ reactivity of ~10 mk is to maintain the reactor critical during a sudden power down to 60% level from a full power equilibrium operation. This capability is considered rather useful and necessary to make the reactor availability high [21]. The other one is simply removing all 21 ADJ rods to gain ~16 mk additional positive reactivity to maximize the Er loading into the CANFLEX fuel.

The amount of Er loading into the central fuel element should be determined such that the negative reactivity by Er is just balanced by the additionally available positive reactivity due to the ADJ rod removal, and the typical discharge burnup of 7,200 MWD/tU can be achieved with the CANFLUX-NU fuel. For the analysis, we have used the non-linear reactivity theory [2,16]. The discharge burnup in the CANDU core is approximately calculated with the non-linear reactivity theory:

$$\int_0^{B_D} \left(\rho(B) - \rho_{loss}\right) dB = 0, \tag{4}$$

where, $B_D$is discharge burnup,$\rho(B)$ is reactivity for burnup, ρ_{loss} is reactivity loss by leakage and parasitic capture by structure materials.

The discharge burnup is decreased by loading Er-mixed fuel because of lowered $\rho(B)$, which can be made up for by reducing the reactivity loss, ρ_{loss}. In other words, the reactivity loss term is reduced by removing adjuster rods from the CANDU6 reactor core.

3. Resultsand Discussions

3.1 2-D lattice calculation results

In order to determine the necessary Er_2O_3 concentration in the central fuel pin, burnup calculations were performed for various concentrations of the Er burnable absorber. The resulting infinite multiplication factor results are shown in Figure 5. Then, corresponding reactivity is fitted into 6th order polynomial function to be used in Eq. (4). From the analysis, two required Er loading are determined to 1.15 w/o and 3.76 w/o, respectively, as shown in Table 2.

In the above depletion calculations for the Er-loaded CANFLEX bundles, the ring-wise fuel temperatures in Table 1 were still used under the assumption that the Er loading in the central fuel rod does not change significantly the fuel temperature. The central power density will be significantly lowered with the Er loading. However, the power sharing of the other rings are hardly affected by the Er loadings. This is because a small amount of Er_2O_3 is only loaded into the single central fuel element only. Therefore, it is expected that the fuel temperature in the outer rings without any Er will not be noticeably affected by the central Er loading. On the other hand, it is well known that the fuel thermal conductivity is slightly degraded with addition of the Er_2O_3 burnable absorber. Thus, the reduction of the central fuel temperature will not be directly proportional to the power density. Therefore, it may be assumed that the fuel temperature in the Er-loaded bundle will not be much different from the reference one.

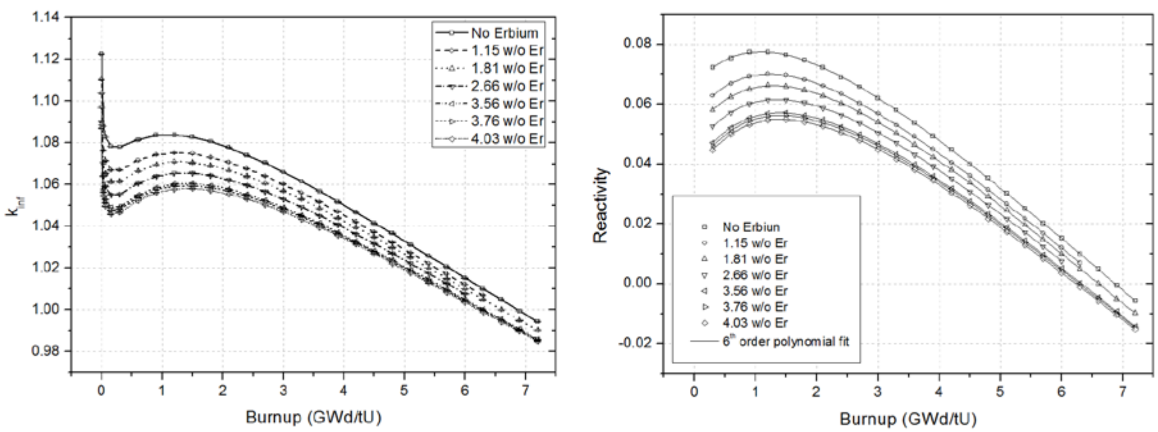

Figure 5. k_{inf}vs. burnup for Er-loaded CANFLEX lattice (left) and its 6th order polynomial fittings (right)

Table 2. The reactivity loss for 7.2 GWd/tU discharge burnup

Erbium Concentration	No erbium	1.15 wt% Er	3.76 wt% Er
ρ_{loss} for $B_D = 7.2$ GWd/tU	47.34 mk	41.90 mk	31.41 mk
$\rho_{loss}^{No\ erbium} - \rho_{loss}$	-	5.44 mk	15.93 mk

The FTC for two different Er_2O_3 concentrations was calculated by using the Serpent code and compared with the FTC of the CANFLEX fuel bundle without any Er burnable absorber. Using 500,000 neutron histories for 150 inactive and 1000 active cycles, the infinite multiplication factor was determined with a standard deviation of ~2 pcm. FTC at the representative fuel temperature is compared in Table 3 and FTC as function of fuel temperature is shown in Figure 6. One can clearly observe that a more negative FTC is obtained with a higher Er concentration in the central fuel pin.

Table 3. Comparison of fuel temperature coefficient at 875.57 K

Erbium Concentration	No erbium	1.15 wt% Er	3.76 wt% Er
Fuel Temperature Coefficient	-0.284 pcm/K	-0.305 pcm/K	-0.350 pcm/K

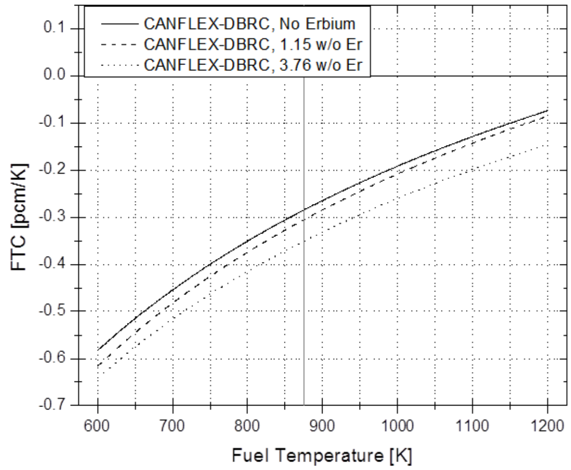

Figure 6. FTC vs. fuel temperature for Er-loaded CANFLEX fuel

To see the effect of theEr_2O_3 loading on the CVR, additional analyses were done for the 3 CANFLEX models and the results are summarized in Table 4. It is noted that CVR is noticeably reduced by a loading of small amount of Er_2O_3 into the central fuel element. This is mainly because the Er burnable absorber suppresses thermal flux increase in the central region in case of the coolant voiding.

Table 4. Comparison of Coolant Void Reactivity with Er-mixed fuel loading

Erbium concentration	Nominal condition		Voided condition		CVR (mk)
	k_{inf}	σ	k_{inf}	σ	
No erbium	0.94646	4.48E-06	0.93084	2.86E-05	**15.62**
1.15 wt%	0.95108	4.52E-06	0.93560	2.89E-05	**15.47**
3.76 wt%	0.96111	4.71E-06	0.94616	3.04E-05	**14.94**

3.2 3-D Time average core analysis result

The time-average core calculation results for different Er_2O_3 concentrations are shown in Table 5. For all cases, effective multiplication factors are slightly super-critical in nominal condition. Therefore, it is confirmed that reactivity compensations from removing adjuster rods are enough for the two chosen erbia concentrations. But at the same time central channel powers exceed the licensed limit. Flattening of the power distribution without ADJ can be achieved with a new zone-wise targeted irradiation pattern. So optimization was performed for case 3.76 wt% of Er_2O_3concentration to get a flattened power distribution and achieve the typical discharge burnup 7,200 GWD/tU.The results of CVR for the optimized irradiation pattern are shown in Table 6. More optimization is needed as the effective multiplication factor is slightly subcritical for the nominal condition.

The CVR evaluation result from time-average core in Table 5 shows a good agreement with that of lattice calculation. Table 6 shows the reduction of CVR is about 1.33mk by using 3.76 wt% erbia. Again, it is shown that the erbia loadingreduces CVR effectively without compromising core performance.The channel power distribution and channel residence time for nominal and 3.76wt%

case are shown in Figures 7 to10. The channel powers in the 3.76 wt% erbia case are below 7000 kW which is within theallowable limit of 7300 kW.

Table 5. Comparison of Coolant Void Reactivity with Er-mixed fuel loading

Erbium concentration	Nominal condition	Voided condition	CVR (mk)
	k_{eff}	k_{eff}	
No erbium	1.0008608	1.0175052	**16.34**
1.15 wt%	1.0005096	1.0164226	**15.65**
3.76 wt%	1.0026612	1.0179385	**14.97**

Table 6. Coolant Void Reactivity with 3.76 wt% Er-mixed fuel loading

Erbium concentration	Nominal condition	Voided condition	CVR (mk)
	k_{eff}	k_{eff}	
No erbium	1.0008608	1.0175052	**16.34**
3.76 wt%	0.9992209	1.0144368	**15.01**

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
A									3101	3239	3335	3334	3241	3107								
B						2777	3341	3825	4037	4179	4229	4230	4185	4048	3838	3356	2792					
C					3128	3652	4212	4657	4938	5054	5037	5042	5065	4954	4676	4233	3675	3157				
D				3243	3854	4484	5018	5397	5616	5673	5610	5617	5689	5638	5423	5046	4515	3892	3284			
E			3143	3854	4552	5126	5549	5827	5968	5978	5899	5908	5998	5993	5859	5585	5167	4602	3906	3191		
F			3778	4472	5092	5531	5797	5962	5985	5977	5926	5936	5999	6015	5999	5841	5583	5152	4537	3842		
G		3464	4266	4983	5456	5767	5907	6004	6030	6028	6027	6038	6052	6063	6046	5959	5829	5527	5061	4346	3549	
H		3922	4734	5398	5752	5966	6057	6120	6119	6111	6124	6135	6136	6154	6167	6116	6038	5831	5488	4830	4027	
J	3276	4240	5133	5728	5983	6091	6216	6276	6235	6194	6188	6198	6219	6272	6327	6280	6168	6071	5829	5244	4362	3379
K	3506	4517	5430	5982	6164	6231	6358	6401	6323	6233	6164	6171	6255	6360	6453	6425	6312	6258	6092	5552	4652	3622
L	3682	4697	5615	6175	6375	6423	6497	6504	6395	6272	6169	6175	6292	6432	6556	6565	6507	6475	6292	5744	4839	3806
M	3703	4731	5670	6263	6497	6547	6594	6577	6456	6329	6224	6229	6348	6492	6629	6662	6632	6599	6381	5800	4874	3828
N	3564	4610	5577	6218	6508	6584	6624	6605	6499	6400	6328	6333	6419	6534	6656	6690	6666	6608	6332	5702	4746	3681
O	3358	4367	5327	6023	6399	6524	6567	6572	6508	6464	6459	6465	6483	6542	6620	6630	6602	6492	6129	5441	4491	3463
P		4056	4924	5658	6080	6328	6410	6467	6469	6471	6491	6496	6489	6500	6511	6467	6399	6163	5752	5022	4163	
Q		3586	4425	5173	5671	6031	6237	6390	6453	6474	6483	6489	6491	6482	6430	6287	6092	5742	5251	4505	3672	
R			3906	4601	5208	5715	6128	6407	6496	6522	6477	6483	6538	6522	6443	6173	5767	5266	4663	3968		
S			3252	3972	4677	5343	5940	6361	6594	6651	6577	6582	6665	6618	6394	5980	5386	4723	4019	3297		
T				3399	4079	4826	5510	6030	6354	6468	6415	6420	6481	6374	6057	5542	4862	4116	3435			
U					3445	4099	4807	5397	5796	5985	5994	5998	5996	5813	5420	4832	4126	3472				
V						3181	3897	4530	4847	5072	5174	5176	5080	4860	4548	3916	3200					

Figure 7. Channel power distribution (kW) for no erbia case

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
A									331	319	310	310	319	330								
B						370	310	271	259	251	248	248	250	258	270	308	368					
C					329	286	249	225	212	207	208	208	207	211	224	247	285	326				
D				317	271	234	209	194	187	185	187	186	184	186	193	208	232	269	313			
E			327	271	230	205	189	180	176	175	178	177	175	175	179	188	203	228	267	322		
F			274	234	206	190	181	176	196	196	198	197	195	195	175	180	188	204	231	270		
G		296	245	210	192	182	198	195	194	194	194	194	194	193	194	197	180	190	207	240	278	
H		264	221	194	182	176	193	191	191	192	191	191	191	190	190	192	174	180	191	217	247	
J	313	246	204	183	175	192	188	180	181	183	183	182	182	180	179	186	190	173	180	200	230	292
K	295	232	193	175	170	188	184	177	179	181	183	183	181	178	175	182	186	168	172	189	216	275
L	281	223	187	170	165	182	180	174	177	180	183	183	180	176	172	178	180	162	167	182	208	261
M	279	221	185	167	162	179	178	172	175	179	182	181	178	174	171	176	177	159	164	181	207	260
N	290	227	188	169	161	178	177	171	174	177	179	178	176	173	170	175	176	159	166	184	212	270
O	306	239	197	174	164	179	178	172	174	175	175	175	174	173	171	177	177	162	171	193	224	285
P		256	213	185	172	166	183	181	181	181	181	180	181	180	180	181	164	170	182	209	239	
Q		286	236	203	185	174	188	183	182	181	181	181	181	181	182	186	172	182	200	232	269	
R			265	228	201	183	171	164	180	180	181	181	179	180	163	170	182	199	225	261		
S			316	263	224	196	176	165	159	158	159	159	157	158	164	175	195	222	260	311		
T				303	256	217	190	174	165	162	163	163	162	164	173	189	216	254	299			
U					252	215	184	164	152	148	147	147	147	152	163	183	213	250				
V						272	224	193	182	174	171	171	174	181	192	223	271					

Figure 8. Channel residence time (FPD) for no erbia case

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
A									3132	3264	3355	3351	3258	3126								
B						2829	3403	3889	4098	4234	4279	4276	4229	4091	3879	3391	2819					
C					3188	3749	4326	4781	5066	5177	5153	5153	5175	5058	4768	4305	3728	3194				
D				3281	3938	4642	5220	5628	5859	5912	5837	5839	5912	5853	5613	5193	4614	3951	3294			
E			3145	3891	4664	5360	5884	6226	6384	6385	6283	6287	6389	6381	6214	5857	5330	4681	3906	3154		
F			3763	4503	5218	5825	6277	6552	6466	6445	6356	6366	6455	6468	6545	6257	5802	5235	4516	3771		
G		3413	4232	5002	5575	6050	6265	6505	6609	6618	6587	6612	6639	6618	6506	6260	6045	5580	5008	4237	3417	
H		3848	4684	5409	5858	6216	6377	6607	6724	6749	6739	6768	6775	6736	6613	6381	6219	5859	5411	4687	3851	
J	3189	4150	5076	5751	6109	6193	6494	6725	6827	6829	6788	6812	6851	6839	6732	6500	6198	6110	5752	5078	4152	3190
K	3402	4414	5373	6042	6378	6395	6634	6822	6889	6841	6721	6728	6850	6897	6829	6640	6400	6379	6043	5374	4415	3403
L	3562	4579	5553	6259	6658	6641	6774	6898	6927	6842	6683	6683	6845	6932	6903	6778	6645	6660	6260	5555	4580	3563
M	3569	4594	5586	6325	6765	6744	6836	6928	6943	6852	6691	6690	6852	6945	6931	6839	6747	6768	6327	5588	4595	3570
N	3420	4451	5452	6211	6678	6684	6791	6894	6926	6868	6749	6747	6868	6927	6896	6793	6686	6680	6212	5454	4452	3421
O	3207	4187	5153	5916	6401	6474	6644	6791	6861	6865	6840	6840	6865	6862	6792	6646	6476	6403	5917	5155	4188	3207
P		3860	4711	5467	5954	6307	6420	6617	6726	6767	6781	6781	6767	6726	6618	6422	6308	5955	5468	4712	3861	
Q		3387	4189	4929	5467	5930	6170	6435	6559	6592	6585	6585	6592	6559	6435	6171	5931	5468	4930	4190	3388	
R			3659	4324	4937	5511	6054	6402	6362	6367	6289	6289	6367	6362	6403	6055	5512	4938	4325	3660		
S			3014	3678	4341	4998	5614	6035	6241	6268	6174	6174	6268	6241	6036	5615	4999	4342	3678	3015		
T				3095	3695	4364	4980	5438	5707	5784	5718	5718	5784	5708	5439	4980	4365	3696	3096			
U					3019	3557	4142	4621	4930	5063	5052	5052	5063	4930	4621	4142	3558	3019				
V						2701	3271	3765	3992	4148	4214	4214	4148	3992	3765	3271	2701					
W									3055	3203	3312	3312	3203	3055								

Figure9. Channel power distribution (kW) for 3.76 wt% erbia case

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
A									274	265	258	258	266	275								
B						304	254	223	213	207	205	205	207	214	223	255	305					
C					270	233	202	183	173	169	170	170	169	173	184	204	235	269				
D				262	222	189	168	156	150	148	150	150	148	150	156	169	190	221	261			
E			273	225	188	163	149	141	137	137	139	139	137	137	141	150	165	187	224	272		
F			230	195	168	150	140	134	223	224	227	227	223	223	134	140	151	167	194	230		
G		251	206	175	157	145	230	222	218	218	219	218	217	218	222	230	145	157	175	206	251	
H		225	187	162	150	141	226	218	215	214	214	213	213	214	218	226	141	150	162	187	225	
J	269	211	173	152	143	233	222	209	205	205	207	206	205	205	208	222	233	143	152	173	210	269
K	254	198	163	145	137	226	217	206	204	205	209	208	205	203	205	217	225	137	145	163	198	254
L	243	191	158	140	132	217	213	203	202	205	210	210	205	202	203	213	217	131	140	158	191	243
M	243	191	157	139	129	214	211	202	202	205	210	210	205	202	202	211	214	129	139	157	191	242
N	253	197	161	141	131	216	212	203	203	204	208	208	204	202	203	212	216	131	141	161	197	253
O	268	209	170	148	137	223	217	207	204	204	205	205	204	204	207	217	223	137	148	170	209	268
P		225	186	160	147	139	225	218	214	213	213	213	213	214	218	225	139	147	160	186	225	
Q		253	209	178	160	148	234	224	220	219	219	219	219	220	224	234	148	160	178	209	253	
R			237	203	178	159	145	137	227	227	229	229	227	227	137	145	159	177	203	237		
S			285	238	202	175	156	145	140	140	142	142	140	140	145	156	175	202	238	285		
T				278	236	201	176	161	154	152	153	153	152	154	161	176	201	236	278			
U					285	246	212	190	178	173	174	173	173	178	190	211	246	285				
V						318	265	230	219	211	208	208	211	219	230	265	318					
W									281	270	261	261	270	281								

Figure 10. Channel residence time (FPD) for 3.76 wt% erbia case

4. Conclusions

The CVR of a CANFLEX-loaded CANDU reactor was successfully reduced by loading erbia (Er_2O_3)into the central fuel pin. Even when erbia burnable absorber is loaded, the typical fuel burnup of ~7,200 MWD/MTU can be achieved by removing the adjuster rods. However, the target fuel exit irradiation should be appropriately adjusted in order to obtain acceptable power profilein the time-average core with reduced number of adjuser rods. Also, the adequacy of2D lattice-based safety parametersare confirmed by showing a good agreement with 3D time-average core calculations. Evlaution of PCR (power coefficient of reactivity) for the eribia-loaded 3D time-average core will be performed in the future work.

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