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Neutronic Evaluation of Super Deep-Burn of PWR TRU Wastes in CANDU with Multi-Recycling Schemes

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1. Introduction

Nuclear power plants (NPP) have contributed to a reliable and cost-effective supply of electricity for decades, on the other hand, a large amount of spent nuclear fuels (SNF) are generated through the continuous operation of the NPPs, which has become one of the most important issues to be urgently resolved in the nuclear industry. Even if a final repository for SNF disposal is established, extremely long-time management is required due to the high radiotoxicity of SNFs. The deep-burn concept [1-3] was proposed to reduce the TRU before the commercialization of fast reactors, in which the burden of final disposal of SNFs can be mitigated by largely reducing the amount of TRU in SNFs. Considering the status of NPPs in South Korea, CANDU is a promising candidate for the deep-burn of TRU due to its current availability in South Korea.

The purpose of this study is to evaluate the super deep-burn of PWR TRU wastes in CANDU with the multi-recycling schemes. The super deep-burn of TRU can be achieved by utilizing an extremely soft neutron spectrum of CANDU with FCM fuels which allow an extremely high burnup due to their excellent structural integrity [4]. Especially, the multi-recycling of fuel rods or extracted TRU was suggested to maximize the TRU consumption performance. The CANFLEX fuel bundle was considered due to its lower average linear power and enhanced heat transfer from fuel to the coolant compared to a standard CANDU fuel bundle [3, 5].

2. Methods and Results

2.1 Computational Method

A Monte Carlo code, called Serpent [6] was used for analyzing CANDU lattice. The discharge burnup was determined based on non-linear reactivity theory with 6th order polynomial fitting. It is assumed that the reactivity loss is 4.3% (4,300 pcm) which is the same value as in CANFLEX lattice with recovered uranium [3, 5]. The final equation to determine the approximate discharge burnup can be written by:

$$\int_0^{BU_d} (\rho(BU) - 4,300) dBU = 0, \qquad (1)$$

where BU_d is the discharge burnup and $\rho(BU)$ is the lattice reactivity (in pcm) as a function of burnup. The Serpent calculation was performed with 100,000 histories, 50 inactive, and 100 active cycles.

2.2 Design Specification of CANFLEX fuel bundle

The CANFLEX fuel bundle considered in this study consists of 43 fuel rods including 8 inner large-rods and 35 outer small-rods. Table I shows the design specification of the CANFLEX fuel bundle and Figure 1 shows the radial configuration of the unit lattice. The fuel bundle power is 12.94 kW/cm [3, 5]. The $TRUO_2$ is loaded in form of FCM in which the $TRUO_2$ kernels are surrounded by four successive buffer layers and are distributed in SiC matrix with 45.0% packing fraction. The isotopic vector of TRU was taken from the PWR SNF which has a discharge burnup of 45 MWD/kg with 30 years cooling time [3, 5].

Table I: Design specification of CANFLEX fuel bundle

Fuel bundle power	1.2939E+04 W/cm
Fuel material	$TRUO_2$
$TRUO_2$ density	10.36 g/cm^3
FCM fuel	
- Kernel radius	175 μm
- Buffer thickness	100 μm
- IPyC thickness	35 μm
- SiC thickness	35 μm
- OPyC thickness	40 μm
- Initial packing fraction	45.0%
- Matrix material	SiC
Inner rod	
- Pellet (radius/temperature)	0.6350 cm/960.16 K
- Cladding (radius/temperature)	0.6710 cm/561.16 K
Outer rod	
- Pellet (radius/temperature)	0.5350 cm/960.16 K
- Cladding (radius/temperature)	0.5680 cm/561.16 K
Coolant area (radius/temperature)	5.17915 cm/561.16 K
Pressure tube (radius/temperature)	5.61266 cm/561.16 K
Gas annulus (radius/temperature)	6.44988 cm/342.16K
Calandria tube (radius/temperature)	5.58954 cm/342.16 K
Moderator area pitch (cm)	28.575 cm

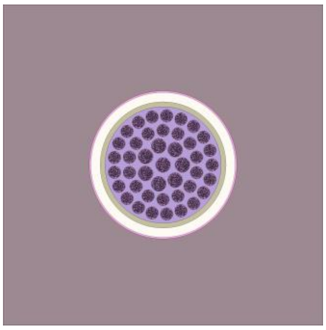


Fig. 1. Radial configuration of CANFLEX unit lattice

2.3 Recycling Scheme

In this study, four recycling cases were considered and compared with the reference case which does not consider recycling. As shown in Table II, two refueling schemes such as 2-batch and 3-batch were considered and two types of recycled material were considered. In the case of fuel rod recycling, fuel rods including all of the fission products and actinides at EOL on the previous campaign were reloaded at different positions in the fuel bundle on the next campaign, while in the case of TRU recycling, TRU extraction from SNFs is required and the extracted TRU is uniformly reloaded in the recycled fuel rods on the next campaign. Throughout all the cases, the maximum standard deviation was estimated to be 62 pcm (at EOL in the 2nd campaign of 2B-TRU).

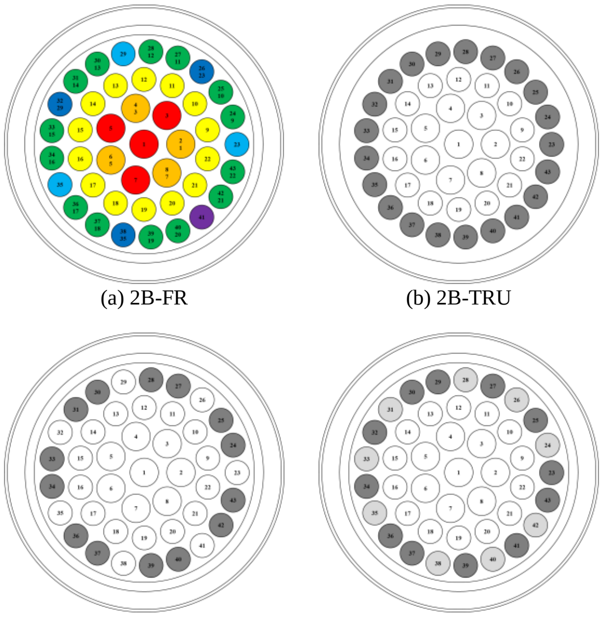
Table II: Case description

Case ID	Refueling scheme	Recycled material
Reference	-	-
2B-FR	2-batch	Fuel rods
2B-TRU	2-batch	TRU
2B-TRU-1	2-batch	TRU
3B-TRU	3-batch	TRU

Figure 3 shows the loading patterns of fuel rods for each case. In 2B-FR, fuel rods including fission products and actinides are recycled with a 2-batch refueling scheme, in which the inner large-rods and outer small-rods are reloaded in the inner-region (i.e., center, and 1st ring) and outer region (i.e., 2nd ring, and 3rd ring) as once-burned fuel rods, respectively, in order to conserve the ring size. In the inner region, 4 inner large-rods in red are reloaded in 4 inner large-rods position in orange. In the outer region, 14 outer-small rods in yellow and 3 outermost small-rods in blue are reloaded in 14 outermost-small rods position in green and 3 outermost small-rods in navy, respectively. The 1 outermost small-rod in purple is not reloaded due to the odd number of small fuel rods, and it is discharged after one irradiation. At the equilibrium campaign, 22 fresh fuel rods are loaded at BOL, and 22 spent fuel rods including 1 once-burned, and 21 twice-burned fuel rods are discharged at EOL.

In 2B-TRU, the TRU extracted from the SNF of the previous campaign is recycled. The TRU extracted from 8 inner large-rods (i.e., center, and 1st ring) and 14 outer small-rods (i.e., 2nd ring) is recycled in 21 outermost small-rods (i.e., 3rd ring) by loading them uniformly. At the equilibrium campaign, 22 fresh fuel rods are loaded at BOL, and 21 twice-burned fuel rods are discharged at EOL. In 2B-TRU-1, the number of fresh fuel rods increases compared to 2B-TRU in order to achieve higher discharge burnup. At the equilibrium campaign, 29 fresh fuel rods are loaded at BOL, and 14 twice-burned fuel rods are discharged at EOL.

In 3B-TRU, a 3-batch refueling scheme was applied with TRU recycling, in which the TRU extracted from 8 inner large-rods (i.e., center, and 1st ring) and 14 outer small-rods (i.e., 2nd ring) is initially recycled in 12 outermost small-rods in dark gray (i.e., 3rd ring). Additionally, the TRU from 12 outermost small-rods in dark gray (i.e., 3rd ring) is recycled once more in 9 outermost small-rods in light gray (i.e., 3rd ring). At the equilibrium campaign, 22 fresh fuel rods are loaded at BOL, and 9 thrice-burned fuel rods are discharged at EOL.



(a) 2B-FR (b) 2B-TRU

(c) 2B-TRU-1 (d) 3B-TRU

Fig. 2. Loading pattern for each case

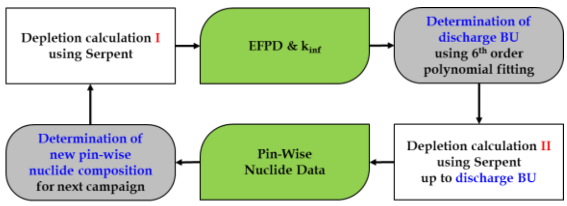


Fig. 3. Calculation procedure for recycling

Figure 3 shows the campaign-by-campaign reload calculation procedure for searching the equilibrium campaign. First, the depletion calculation is performed to determine discharge burnup based on non-linear reactivity theory with the 6th order polynomial fitting, and then the second depletion calculation is performed up to the discharge burnup. From the second depletion calculation, pin-wise nuclide mass data at the discharge burnup is extracted and new pin-wise nuclide composition is determined for the next campaign. The determination procedure of the new pin-wise nuclide composition is varied depending on the recycling scheme. In the case of fuel rod recycling, all of the fission products and actinide in each fuel rod to be recycled are conserved from EOL in the previous campaign to BOL in the next campaign, while in the case of TRU recycling, it is assumed that all of the fission products in fuel rods to be recycled are removed and TRU nuclides are recycled by loading them uniformly in once-recycled fuel rods at BOL in the next campaign. The campaign-by-campaign reload analyses were performed to search the equilibrium campaign, in which the neutronic characteristics are converged.

2.4 Neutronic Characteristics Analyses

Figure 4 shows the comparison of the k_{inf} curves during depletion for the equilibrium campaigns of all cases. As shown in the figure, the life time decreased in recycling cases from 846 EFPD in the reference case to 428 EFPD, 504 EFPD, 655 EFPD, and 532 EFPD in 2B-FR, 2B-TRU, 2B-TRU-1, and 3B-TRU, respectively. The degradation in life time was evaluated to be the largest in 2B-FR due to the large neutron absorption of fission products. The life time degradation was mitigated by recycling only TRU, and further improvement was shown in 2B-TRU-1 due to a large number of fresh fuel rods.

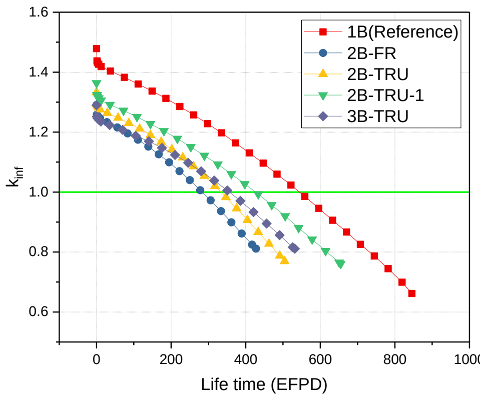


Fig. 4. Comparison of k_{inf} for the Eq. campaigns

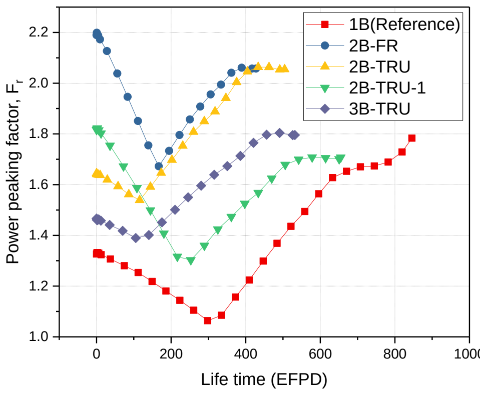


Fig. 5. Comparison of F_r for the Eq. campaigns

The radial power peaking factors are depicted in Fig. 5. As shown in the figure, the power peaking factors for all cases decreased from BOL to MOL and rebounded up from MOL to EOL. For all the cases, the power peaking moved from the outer rods at BOL to central rods at EOL. The power peaking factors of recycling cases were evaluated to be higher than the reference case due to the varied fuel composition between fuel rods in the lattice caused by the recycling. Nevertheless, 2B-TRU-1 showed a significant improvement in power peaking compared to 2B-TRU by increasing the number of fresh fuel rods with in/out loading pattern. In the case of 3B-TRU, the maximum power peaking factor was evaluated to be 1.80 at EOL which is similar level to that of the reference case (i.e., 1.78 at EOL). The high power peaking also can be accommodated by decreasing reactor power for a special purpose for TRU transmutation.

The normalized neutron spectra at BOL are depicted in Fig. 6 for all cases. The conventional case using natural uranium (NU) was plotted together. It is noted that the TRU-loading cases have harder neutron spectra than the NU-loading case due to the large thermal absorption of TRU. From the results of the reference case, 2B-TRU, and 2B-TRU-1, it can be seen that the neutron spectra were evaluated to be harder as the amount of fresh TRU increased. In the case of 2B-FR, even though it has a lower amount of fresh TRU than 2B-TRU, the neutron spectrum was evaluated to be harder due to the large absorption of fission products. The 3B-TRU case showed a similar neutron spectrum to the 2B-FR case.

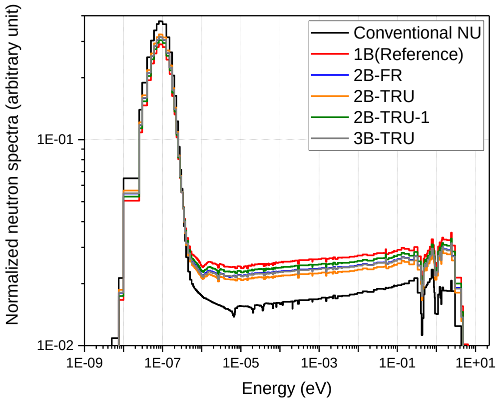


Fig. 6. Comparison of neutron spectra at BOL

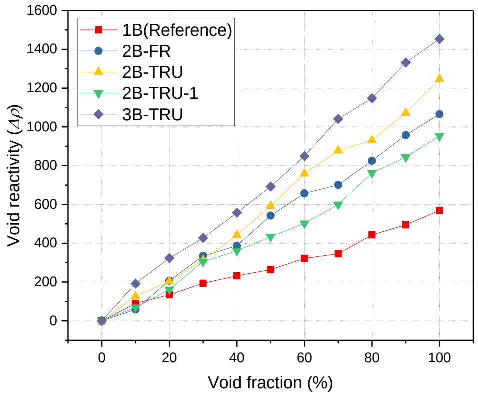


Fig. 7. Comparison of coolant void reactivity at BOL

One of the important safety parameters of CANDU reactors is coolant void reactivity which is a positive value due to the unique configuration of the CANDU fuel bundle. Figure 7 shows the comparison of the coolant void reactivity for each case. As shown in the figure, the void reactivities are evaluated to be higher in recycling cases than in the reference case. The 3B-TRU case has the highest reactivity insertion of 1,453 pcm at total voiding, followed by 1,247 pcm of 2B-TRU, 1,066 pcm of 2B-FR, 953 pcm of 2B-TRU-1, and 569 pcm of the reference case. These strong positive void reactivities should be addressed in future work.

2.5 TRU Mass Flow Analyses

Figure 8 shows the TRU mass change during the residence time. For 2B-FR, 2B-TRU, and 2B-TRU-1, the TRU mass changes were shown over two campaigns, and for 3B-TRU, the TRU mass changes were shown over three campaigns. As shown in Fig. 8, the most of TRU were consumed at the 1st campaign and the TRU consumption rates were evaluated to significantly decrease with recycling. The percent changes in TRU consumptions are summarized in Table III. In the comparison between the reference and 2B-FR, it is noted that 2B-FR has a lower TRU consumption in spite of the longer residence time than the reference, which means that the recycling of fuel rods is not effective for TRU consumption due to a large neutron absorption by the fission products. On the other hand, 2B-TRU, 2B-TRU-1, and 3B-TRU showed excellent TRU consumption performances compared to the reference case, in which the percent change in TRU mass was evaluated to be 75.91%, 77.12%, and 79.97%, respectively.

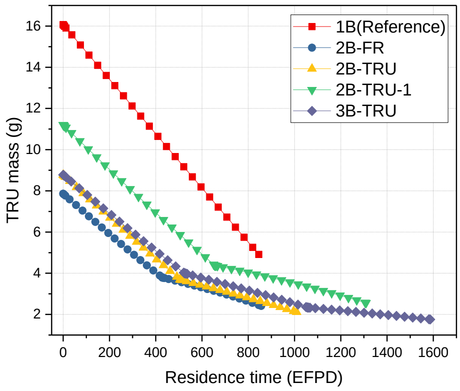


Fig. 8. TRU mass change during residence time

3. Conclusions

In this study, a super deep-burn of TRU utilizing CANDU reactor has been investigated by using the FCM fuel. In particular, the multi-batch refueling scheme with the fuel rod or TRU recycling was considered to achieve further improvement in TRU consumption performance. From the analyses, it has been found that the recycling of fuel rods was not effective in terms of TRU consumption. On the other hand, in the case of TRU recycling, considerably high TRU consumption can be achieved by applying 2-batch and 3-batch refueling schemes. In the 2-batch refueling scheme with TRU recycling, the percent change in the TRU consumption was improved from 75.91% for 2B-TRU to 77.12% for 2B-TRU-1 by increasing the ratio of the number of fresh fuel rods to the number of recycled fuel rods. It is remarkable that a considerably high TRU consumption of 79.97% was achieved by applying a 3-batch refueling scheme with TRU recycling. It is concluded that super deep-burn of TRU with the significantly improved TRU consumption can be achieved in CANDU by using FCM fuel with the TRU multi-recycling scheme.

Table III: Comparison of residence time and TRU consumption performance

Case ID	Discharge BU (MWD/kg)	Residence time (EFPD)	TRU consumption	
Reference	681.30	846	[a]Charge (g)	16.07
			[b]Discharge (g)	4.91
			Consumed (g)	11.16
			Consumed (%)	69.44
2B-FR	[c]674.67	856	[a]Charge (g)	8.21
			[b]Discharge (g)	2.56
			Consumed (g)	5.65
			Consumed (%)	68.85
2B-TRU	[d]567.92 /419.07	1008	[a]Charge (g)	8.78
			[b]Discharge (g)	2.11
			Consumed (g)	6.66
			Consumed (%)	75.91
2B-TRU-1	[d]597.22 /406.79	1310	[a]Charge (g)	11.21
			[b]Discharge (g)	2.56
			Consumed (g)	8.64
			Consumed (%)	77.12
3B-TRU	[d]533.63 /407.11 /244.29	1064	[a]Charge (g)	8.78
			[b]Discharge (g)	1.76
			Consumed (g)	7.02
			Consumed (%)	79.97

[a]TRU in fresh fuels at BOL
[b]TRU in discharged fuels at EOL
[c]Accumulated discharge burnup during residence time
[d]Discharge burnup for each batch

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REFERENCES

[1] C. Rodriguez et al., “Deep-burn: making nuclear waste transmutation practical,” Nuclear Engineering and Design, 222, 299-317, 2003.
[2] Y. Kim, F. Venneri, “Optimization of one-pass TRU deep-burn in modular helium reactor,” Nuclear Science and Engineering, 160, 59-74, 2008.
[3] D. Hartanto, Y. Kim, and F. Venneri, “Neutronic evaluation of a super-deep-burn with TRU Fully Ceramic Microencapsulated (FCM) fuel in CANDU,” Progress in Nuclear Energy, 83, 261-269, 2015.
[4] F. Venneri et al., “Fully Ceramic Microencapsulated Fuels: A Transformational technology for Present and Next Generation Reactors,” Transaction of the American Nuclear Society, 104, 671-674, 2011.
[5] B. Hyland, and G. R. Dyck, “Actinide burning in CANDU reactors,” In: Proceedings of GLOBAL 2007, Boise, Idaho, United States, September 9-13, 2007.
[6] J. leppänen, “Serpent – a Continuous-nergy Monte Carlo Reactor Physics Burnup Calculation Code User’s Manual,” VTT Technical Research Centre of Finland, 2015.