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Neutronic Analysis of Advanced SFR Burner Cores using Deep-Burn PWR Spent Fuel TRU Feed

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1. Introduction

In this work, an advanced sodium-cooled fast TRU (Transuranics) burner core using deep-burn TRU feed composition discharged from small LWR cores was neutronically analyzed to show the effects of deeply burned TRU feed composition on the performances of sodium-cooled fast burner core. We consider a nuclear park that is comprised of the commercial PWRs, small PWRs of 100MWe for TRU deep burning using FCM (Fully Ceramic Micro-encapsulated) fuels[1,2], and advanced sodium-cooled fast burners[3] for their synergistic combination for effective TRU burning. In the small PWR core having long cycle length of 4.0 EFPYs, deep burning of TRU up to 35% is achieved with FCM fuel pins whose TRISO particle fuels contain TRUs in their central kernel. This small long cycle PWR core consists of new special fuel assemblies having both UO_2-ThO_2 fuel pins and FCM fuel pins. The FCM fuel[4,5,6] has been characterized as one of the accident-tolerance fuel candidates by its high burnup performances due to its extraordinary fission product retention in the multiple buffer layers and by its low fuel temperature due to SiC matrix. In the nuclear park we are considering, high radiotoxicity TRUs are discharged from the commercial PWRs and they are reprocessed and fabricated as FCM fuel which is charged into the small PWR cores where they are deeply burned with a single pass without recycling. The small LWRs have been designed to have net consumer of TRUs having net TRU destruction rate of ~25%, which means that the amount of destructed TRUs in FCM pins is much larger than those of the generated TRUs in UO_2-ThO_2 pins. In these small PWRs, TRUs are discharged both from the UO_2-ThO_2 pins and the FCM pins but these TRUs discharged from two different fuel pins have different characteristics in the TRU compositions and the radiotoxicities including heat generation. The discharged TRUs from small PWR cores are then reprocessed and then charged into the advanced SFR burner cores where the fuel cycle is closed by recycling all the actinides.

In this work, we first analyzed the radiotoxicity and heat generation characteristics of the TRUs discharged from UO_2-ThO_2 pins and FCM pins. Then their characteristics were compared with those of the typical PWRs. Then, the neutronic characteristics and performances of the advance SFR burner cores with TRU feed from small LWRs are analyzed in detail. In addition, we analyzed the effects of the cooling time of spent fuel discharged from small deep-burn LWR cores.

In Sec. 2, the computational methods and models are described. In Sec. 3, the detailed comparative neutronic analyses of the advanced SFR burner cores are performed and their performances are inter-compared. Also, we performed comparative BOR (Balance of Reactivity) analysis to check the inherent safety of the cores.

2. Computational Methods and Models

The REBUS-3 equilibrium model[7] with a nine group cross section was used to perform the core depletion analysis where the feed TRU contents are searched such that k-eff at EOEC (End of Equilibrium Cycle) is 1.005. The nine group cross section were produced by collapsing the 180 group cross sections with the 150 group core region-wise neutron spectra that were calculated with TWODANT R-Z geometrical model[8]. The 150 group cross section library of ISOTXS format is generated using TRANSX code[9] and a MATXS format which was generated with the NJOY code for master nuclides. The core physics parameters were evaluated with 80 group cross section and DIF3D HEX-Z nodal option[10]. The decay chain spans the range from ^{232}Th to ^{246}Cm. We assumed 99.9% and 5% recovery for actinides and rare earth fission product, respectively, and the other fission products are assumed to be completely removed to waste stream during reprocessing.

3. Core Performance Analysis

3.1 TRU Feed Characteristics

In this work, we considered several different types of TRU feeds including typical PWR spent fuel TRU. The TRU feed from the small deep-burn PWR spent fuel is classified into 1) TRUs from FCM fuel pins, and 2) TRUs from UO_2-ThO_2. As described in Ref. 1 and 2, the FCM fuel pins have very high discharge burnup higher of 300MWD/kg ~ 400MWD/kg because TRISO kernels of FCM pins contain only a small amount of TRUs for deep-burning. On the other hand, the UO_2-ThO_2 fuel pins have low discharge burnup of 30~40MWD/kg and the uranium enrichments are 16wt% and 13.5wt%. The contents of ThO_2 in the UO_2-ThO_2 fuel pins are 50wt% and 60wt% for two different type fuel assemblies of the final design of the small PWR core. For comparison, we also considered the reference TRU composition of the PWR spent fuel of 55 MWD/kg and 10years cooling. Table 1 compares the TRU feed compositions considered in this work. In Table 1, the TRU compositions from FCM pins and UO_2-ThO_2 pins of the small long cycle PWR core correspond to the core average compositions. As shown in Table 1, the TRU feed from FCM pins has the lowest fissile plutonium contents due to its highest burnup while the one from UO_2-ThO_2 pins has the highest fissile plutonium content due to its lowest burnup. These differences will give significant differences on the performances of SFR burner cores. In analyzing the SFR burner core performances, we neglected Cm-243, Cm-245, and Cm-246 due to their very small contents in spent fuel.

Table 1: Comparison of TRU feed compositions (10 years cooling)

Nuclide	From PWR	FCM pins	UO_2-ThO_2 pins
Np-237	6.02	5.88	7.44
Pu-238	2.81	8.76	1.81
Pu-239	43.59	22.16	60.97
Pu-240	21.95	29.64	14.49
Pu-241	13.42	13.37	11.67
Pu-242	7.65	9.84	2.41
Am-241	0.43	4.55	0.60
Am-242	0.00	0.00	0.00
Am-243	2.21	3.05	0.40
Cm-242	0.18	0.58	0.00
Cm-244	0.96	2.16	0.20

Next, we compared the radiotoxicities (Curies/kg) and heat generations (W/kg) as the functions of the cooling time after discharge for the TRU feeds described in Table 2. Fig. 1 and Fig. 2 compare the radiotoxicities and thermal heat generations versus cooling time, respectively. The most significant contribution to radiotoxicity is from Pu-241 which has the shortest half-life of 14.35 years among plutonium isotopes. So, the TRUs from UO_2-ThO_2 pins have the smallest radiotoxicity. The next strong contributions come from Pu-238 and Cm-244. With these facts, TRUs from FCM pins have the largest radiotoxicity and the ones from UO_2-ThO_2 pins the smallest radiotoxicity.

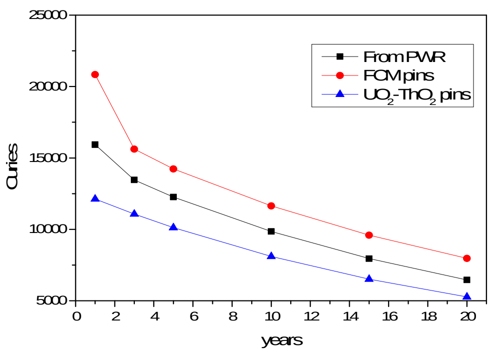

Fig. 1. Comparison of radiotoxicities versus cooling time

The heat generations from these TRUs have similar trends to those of radiotoxicities but they slowly change after 3 years cooling.

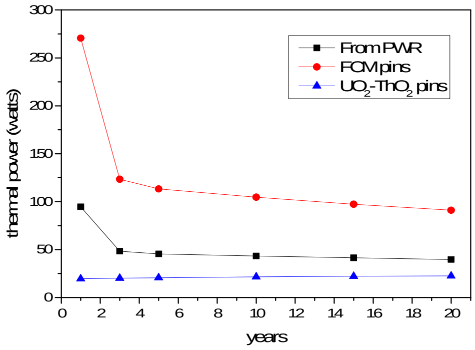

Fig. 2 Comparison of thermal heat generations versus cooling time

3.2 Description of the SFR Burner Core Design

The SFR burner core design is from our previous study[3]. The core configuration is shown in Fig. 3 and the basic design parameters are given in Table 2. The rating of the core is 400MWe. The refueling interval is one year (the cycle length 332 EFPDs) with ~90% capacity factor. The ternary metallic fuel of TRU-U-10Zr with 75% smear density for fuel swelling is considered as fuel. The active core consists of 108 inner driver and 84 outer driver fuel assemblies. This core is featured by the special assemblies having thick duct and small number of fuel rods to achieve power flattening under uniform charge fuel composition and by the axially central absorber (B_4C) region and $ZrH_{1.8}$ moderator rods to improve the core performances. The axial configuration is shown in Fig. 4 and the detailed description of the core is given in Ref. 3. In particular, the axially central B_4C absorber was introduced to increase TRU burning ate and to reduce sodium void reactivity worth by increasing the absorption of the neutrons leaking through active core region under sodium voiding. The active core height is 90cm and central absorber thickness is 25cm. The thickness of the axial absorber region was selected through a parameter study in the previous study.

Table 2: Basic Design Parameters of the cores

Design parameters	**Specification**
Power [MW(electric)/MW(thermal)]	400/1015.6
Cycle length (EFPD)	332
Fuel type	TRU-U-10Zr
Number of rods per FA	[a]**271/217**
Smear density of fuel	75% TD
Duct wall thickness (mm)	[a]**3.7/11.5**
Assembly pitch (cm)	16.22
Rod outer diameter (mm)	7.5
Clad thickness (mm)	0.53

[a]Values for the normal and thick duct assemblies

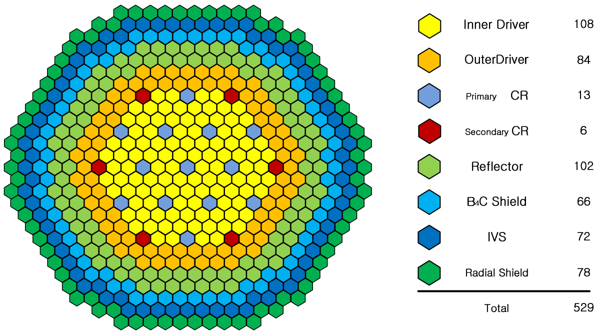

Fig. 3. Configuration of the SFR burner core

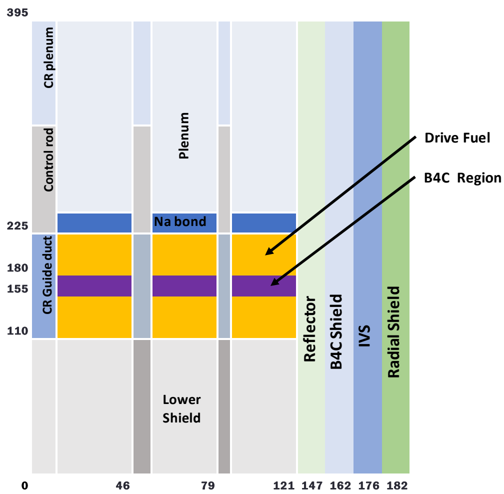

Fig. 4. Axial cutview of the cores having B_4C region

3.3 Core Performance Analysis

First, we analyzed the performances of the SFR burner core using TRU feeds from FCM fuel pins of small long cycle PWR deep-burn core and the typical PWRs. For the TRU feed from FCM fuel pins of small long cycle PWR deep-burn core, we analyzed the effect of the cooling time by considering four different cooling times of 5, 10, 15, and 20 years. Table 3 summarizes the main performance parameters including sodium void reactivity worth. As shown in Table 3, the SFR burner core using TRU feed from FCM pins has significantly smaller burnup reactivity swing by 765pcm, higher TRU conversion ratio by 24%, and higher TRU burning rate by 8.7% for the same 10 years cooling time than the one using TRU feed from typical PWR core. On the other hand, the SFR burner core using TRU feed from FCM pins has larger sodium void worth by ~462 pcm than the corresponding one using TRU feed from typical PWR core. These difference features of the core performances are resulted from the fact that the low fissile plutonium content of TRU feed from FCM pins leads to higher TRU contents in fuel and the higher breeding of TRUs. In particular, the reduction of the burnup reactivity swing is from the higher conversion ratio. For different cooling times, the SFR burner core using TRU feed with longer cooling time has smaller burnup reactivity swing, larger TRU conversion ratio, larger sodium void reactivity worth and higher TRU burning rate due to the reduction of the fissile plutonium content in feed composition than the one using TRU feed with shorter cooling time. The reduction of fissile plutonium content in TRU feed composition for longer cooling time is mainly due to the beta decay of Pu-241 into Am-241 with a relatively short half-life of 14.35 years.

Table 2: Comparison of the performances of SFR burner core having different TRU feeds (cooling time effect)

Parameters	Reference	Case A-1	Case A-2	Case A-3	Case A-4
Feed TRU type	PWR	FCM pins	FCM pins	FCM pins	FCM pins
Cooling time (year)	10	5	10	15	25
Average conversion ratio	0.5466	0.6654	0.6773	0.6869	0.6945
Burnup reactivity swing (pcm)	3409	2771	2643.5	2540	2470
Average discharge burnup (MWD/kg)	103.2	103.2	103.2	103.2	103.2
TRU wt% in HM (BOEC/EOEC)	48.0/47.3	56.4/55.8	57.2/56.6	57.8/57.3	58.4/57.8
HM inventory (BOEC/EOEC, kg)	12174/11825	12177/11827	12177/11828	12178/11828	12178/11829
TRU inventory (BOEC/EOEC, kg)	5842/5598	6869/6605	6961/6695	7040/6773	7110/6841
TRU consumption rate (kg/cycle)	246.9	268.1	270.1	271.8	273.3
TRU support ratio	2.62	2.85	2.87	2.89	2.90
Uranium consumption rate (kg/cycle)	103.6	83.3	81.4	79.8	78.3
3D power peaking factor (BOEC/EOEC)	1.75/1.51	1.78/1.57	1.78/1.58	1.78/1.59	1.79/1.59
Average power density(W/cm^3)	251.3	251.3	251.3	251.3	251.3
Peak average linear power(W/cm, BOEC/EOEC)	464.9/380.7	460.8/393.9	459.5/396.9	457.8/400.1	459.7/398.6
Fast neutron fluence (n/cm^2)	2.55×10^{23}	2.55×10^{23}	2.55×10^{23}	2.55×10^{23}	2.55×10^{23}
Total sodium void worth (pcm, BOEC)	667.2	1077	1129.5	1171	1206

Table 3 compares the performances of the SFR burner cores using three different TRU feed compositions. The first one is from the typical PWR cores, the second and third ones are from FCM fuel pins and UO_2-ThO_2 pins of the small long cycle PWR deep-burn cores. These three TRU compositions have the same cooling time of 10 years. As expected from their discharge burnup, the SFR burner core using TRU feed from UO_2-ThO_2 pins has the smallest TRU conversion ratio, the largest burnup reactivity swing, the lowest TRU burning rate, and the lowest sodium void reactivity worth, which are resulted from the low fissile plutonium contents in the TRU feed due to the low discharge burnup. Fig. 5 compares the neutron spectra of these three cases having different TRU feed compositions. As shown in Fig. 5, the SFR burner core using TRU feed from FCM fuel has the hardest core spectrum due to the highest neutron absorption from the highest TRU contents.

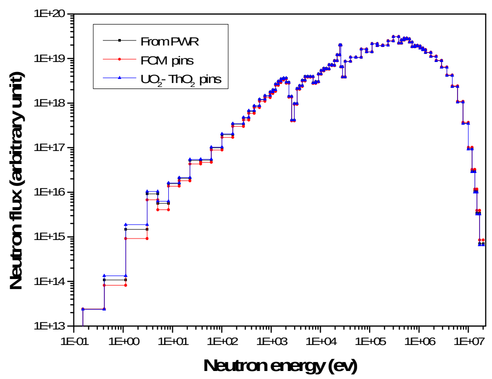

Fig. 5. Comparison of the core neutron spectra

Tale 4 compares the temperature reactivity coefficients and control rod worth of the SFR burner cores using three different TRU feed compositions considered in Table 3. Table 4 shows that of three considered cases, the SFR burner core using TRU feed from UO_2-ThO_2 pins has the most negative Doppler coefficient, the smallest reactivity coefficient by coolant expansion, and the largest control rod worth. On the other hand, the SFR burner core using TRU feed from FCM pins has the least negative Doppler coefficient, the largest reactivity coefficient by coolant expansion, the most negative reactivity coefficient by fuel axial expansion and the smallest control rod worth. These differences in the reactivity coefficients directly lead to the differences in the inherent safety features which were analyzed using BOR.

Table 3: Comparison of the performances of SFR burner core having three different TRU feeds

Parameters	Reference core	Case A-2	Case B-1
Feed TRU type	PWR	FCM pins	UO_2-ThO_2 pins
Cooling time (years)	10	10	10
Average conversion ratio	0.5466	0.6773	0.5009
Burnup reactivity swing (pcm)	3409	2643.5	3753
Average discharge burnup (MWD/kg)	103.2	103.2	103.2
TRU wt% in HM (BOEC/EOEC)	48.0/47.3	57.2/56.6	43.5/42.8
HM inventory (BOEC/EOEC, kg)	12174/11825	12177/11828	12173/11824
TRU inventory (BOEC/EOEC, kg)	5842/5598	6961/6695	5291/5057
TRU consumption rate (kg/cycle)	246.9	270.1	236.3
TRU support ratio	2.62	2.87	2.51
Uranium consumption rate (kg/cycle)	103.6	81.4	113.7
3D power peaking factor (BOEC/EOEC)	1.75/1.51	1.78/1.58	1.74/1.48
Average power density(W/cm^3)	251.3	251.3	251.3
Peak average linear power(W/cm, BOEC/EOEC)	464.9/380.7	459.5/396.9	467.1/374.0
Fast neutron fluence (n/cm^2)	$2.55x10^{23}$	$2.55x10^{23}$	$2.54x10^{23}$
Total sodium void worth (pcm, BOEC/EOEC)	667.2/654.8	1129.5/1125.4	460.2 / 437.4

Table 4: Comparison of the reactivity coefficients and BOR analyses

Parameters	Reference core	Case A-2	Case B-1
Fuel Axial expansion (pcm/K)			
Fuel only	-0.269 / -0.285	-0.319 / -0.332	-0.247 / -0.264
Fuel+clad	-0.147 / -0.157	-0.160 / -0.168	-0.141 / -0.151
Radial expansion (pcm/K)	-1.014 / -1.064	-1.017 / -1.056	-1.037 / -1.094
Sodium coolant expansion (pcm/K)	0.189 / 0.164	0.342 / 0.325	0.121 / 0.09
Fuel Doppler coefficient (pcm/K, 900K)	-0.379 / -0.389	-0.271 / -0.278	-0.421 / -0.438
Control rod worth (pcm)	10904 / 10749	9888 / 9821	11330 / 11144
Primary	9300 / 9025	8408 / 8255	9675 / 9352
Secondary	1604 / 1724	1480 / 1566	1655 / 1792
Effective delayed neutron fraction	0.00290 / 0.00292	0.00279 / 0.00280	0.00292 / 0.00293
Neutron life time (μsec)	0.313 / 0.317	0.272 / 0.277	0.329 / 0.332
A (pcm)	-97.2	-88.5	-100.2
B (pcm)	-192.74	-176.86	-203.13
C (pcm/℃)	-1.473	-1.265	-1.584
A / B	0.504	0.500	0.493
$C \Delta T_c / B$	1.185	1.111	1.209
$\rho_{TOP} / \lvert B \rvert$	1.878	1.586	1.961
Number of CRs required for self-controllability	25	21	26

In the BOR analysis, we assumed uncertainties of 20% in burnup reactivity swing for conservativism. The results of BOR analysis are also included in Table 4. Also, we did not consider the negative reactivity coefficient from the expansion of the control rod driveline. In Table 4, six quantities are evaluated by using the temperature reactivity coefficients to check the self-controllability with BOR analysis. To satisfy the self-controllability, the first three quantities *A*, *B*, and *C* should be negative and the following condition should be met :

$$\begin{aligned} &A / B \le 1.0, \\ &1.0 \le C\Delta T_c / B \le 2.0, \\ &\Delta\rho_{TOP} / B < 1.0. \end{aligned} \quad (1)$$

The results of BOR analysis given in Table 4 shows that all the three cores satisfy all of the conditions for self-controllability except for the last condition which is associated with unprotected transient overpower (UTOP). To meet this last condition, the burnup reactivity swing should be reduced or the quantity *B* should be increased in its absolute value or the number of control rods should be increased to reduce the reactivity worth vested on a single control rod assembly in order to suppress the initial excess reactivity. In this work, the number of control rod assemblies required to satisfy the last condition associated with UTOP are estimated with the assumption of the linearity between $\Delta\rho_{TOP}$ and the number of control rod assemblies. The results show that the SFR burner core using TRU feed from FCM fuel pins of the small long cycle PWR deep-burn core has the smallest number of control assemblies which is required to satisfy all the conditions of the self-controllability.

4. Summary and Conclusions

In this paper, we analyzed the performances of the advanced SFR burner cores using TRU feeds discharged from the small long cycle PWR deep-burn cores. Also, we analyzed the effect of cooling time for the TRU feeds on the SFR burner core. The results showed that the TRU feed composition from FCM fuel pins of the small long cycle PWR core can be effectively used into the advanced SFR burner core by significantly reducing the burnup reactivity swing which reduces smaller number of control rod assemblies to satisfy all the conditions for the self-controllability than the TRU feed composition discharged from the typical PWR cores. Also, the TRU feed from FCM fuel pins of the small long cycle PWR core increases TRU burnup rate.

From the study done in this paper, it can be concluded that the advanced SFR burner core using TRU feed FCM fuel pins of the small long cycle PWR core can be designed by increasing the number of control rod assemblies up to 21 to satisfy all the conditions for the self-controllability, which means the inherent safety. These results show that the advanced SFR burners can be coupled with the small long cycle PWR deep-burn cores to effectively incinerate TRUs from the current LWRs.

Acknowledgement

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