Neutronic Study on Sodium-cooled Fast Burner Cores having Proliferation-Resistance Thorium and Depleted-Uranium based Blankets

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1. Introduction

To meet the increasing energy demand, the role of nuclear power is expected to be continued in the future. Currently, lots of spent fuels have been discharged from these LWRs and they have been stored in interim storage facilities. So, the appropriate management of the highly radioactive wastes discharged from LWRs is one of the most important issues in nuclear industry. Recently, we have suggested advanced sodium-cooled TRU burner cores with uranium-free metallic fuels [1,2] and thorium blankets [3,4] to achieve a very high TRU burning rate. Our previous work showed that the thorium blankets loaded in the axial core region are effective in reducing burnup reactivity swing and improving the Doppler coefficient with a slight reduction of TRU support ratio.

The objective of this work is to analyze the performance of the new blankets and to assess the proliferation resistances [5,6] of the blankets in the uranium-free fueled burner cores.

2. Performances of SFR Burner Cores

2.1 Description of SFR Burner cores

The reference configuration and the R-Z cut view of SFR core are shown in Fig. 1. The active core height of the reference core is 90cm and it rates 1015.6MWth (400MWe). As shown in Fig. 1(left), the core consists of two radial regions (i.e., inner and outer regions). These two core regions have different fuel assembly types. The fuel assemblies in inner core region consist of 9 rings of fuel rods (i.e., 217 fuel rods) and it has a thick duct of 10.7mm while the outer core fuel assemblies consist of 10 rings of fuel rods (i.e., 271 fuel rods) with same assembly pitch. The fuel assembly having thick duct are loaded in inner core region to improve the TRU burning rate and to achieve power flattening under a single feed composition by reducing the fuel volume fractions. The ternary metallic fuels of TRU-W-10Zr are considered to improve the Doppler coefficient by adding resonant nuclides. As shown Fig. 1(right), the thorium blankets or depleted uranium blankets are axially loaded in central core regions to reduce burnup reactivity swing and to improve the Doppler effects by partially adding the fertile resonant nuclide. In addition, we replaced 12 fuel rods with moderator ($ZrH_{1.8}$) rods to improve the Doppler coefficient, to reduce burnup reactivity swing by the increase of heavy metal inventory due to higher capture rate resulted from spectrum softening and to reduce the sodium void worth. Table I summarized the main design parameters. The core depletion analysis was performed with 9 group cross section and REBUS-3 equilibrium cycle model [7]. The core physics parameters were evaluated with 80 group cores section and DIF3D HEX-Z nodal option [8]. We assumed 99.9% and 5% recovery for actinides and rare earth fission product during reprocessing, respectively while outer fission product are assumed to be completely removed. The composition of TRU feed used in this work is the TRU composition of LWR spent fuel having 50MWD/kg and 10 year cooling.

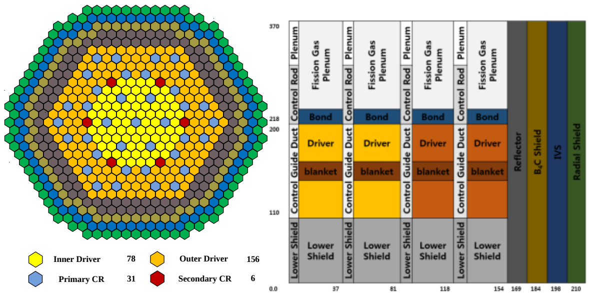

Fig. 1. Configuration of the SFR burner core

Table I Design parameters for the reference core

Design parameter	Specification
Power (MWe/MWt)	400/1015.6
Active core height(cm)	90
Driver fuel type	TRU-W-10Zr
Blanket fuel type	Th-10Zr DU-10Zr
Number of rods per FA(outer/inner)	271 /217
Smear density of fuel	75%
Duct wall thickness(mm, outer/inner)	3.7 / 11.5
Assembly pitch (cm)	16.22
Rod outer diameter(mm)	7.5
Wire wrap diameter(mm)	1.4
Clad thickness(mm)	0.53
Fuel cycle length (EFPD)	332
Number of fuel management batches	
Driver	4
Blanket	4

2.2 Thorium or Depleted Uranium Blankets

First, we analyzed the cores having 18cm thick axially central thorium or depleted uranium blankets. The performances of these cores are compared with those of the reference cores having no blankets. As shown in Table II, the cores having thorium or depleted uranium blankets have smaller burnup reactivity swing by 1587pcm (i.e. 28.9%) and 1800pcm (32.8%) than that of the reference core having no blanket, respectively. These significant reductions of the burnup reactivity swing are resulted from the increase of heavy metal loading (i.e., reduction in discharge burnup). In particular, the core having axial depleted uranium blankets have lower discharged burnup by ~ 12.9% than the core having axial thorium blankets due to a larger uranium inventory.

The use of moderator rods lead to a slight reduction of the burnup reactivity swing due to the increase of initial TRU inventory resulted from the higher neutron absorption through spectrum softening. As expected, the use of moderator rods substantially improves the Doppler coefficients. In addition, the sodium void reactivity worths were considerably reduced with the use of moderator rods. All the cores have very high TRU support ratio larger than 3.417. This fact means that these cores can consume the amount of TRUs discharged from 3.417~3.75 PWRs of the same thermal power and cycle length. The small reduction of TRU support ratios are due to the fissile nuclide generation in the blanket. These results means that the uses of axial thorium and depleted uranium blankets are very effective in improving the performances of uranium-free burner cores.

2.3 Proliferation-Resistant Blankets

The use of blanket (thorium or uranium) produces in the generation of high fissile concentration material (i.e., ^{233}U, ^{239}Pu and ^{241}Pu) and so the issues of the proliferation resistance are important. In particular, this high fissile concentration (^{233}U) in thorium blanket can generate nuclear proliferation issues even if the radioactive decays of ^{232}Th and subsequent (n,2n) reactions generate the strong gamma emitters such as ^{208}Tl and ^{208}Pb. In order to improve the proliferation resistance of the discharged blankets of our SFR burner cores, the several different blankets are considered by adding depleted uranium (DU) and TRU from LWR spent fuel.

First, depleted uranium (DU) is considered to be added into the thorium blanket, which dilutes the fissile concentration. But it is expected that the addition of DU into the blanket leads to the production of high quality plutonium which can be the other proliferation issues. To dilute the fissile concentration in the plutonium inside the blanket, it is considered to add small amount of TRUs contained in the LWR spent fuel. For DU blanket, the TRUs are added into the depleted uranium blanket to dilute the fissile concentration in the plutonium. The proliferation resistance of the discharged spent blankets from the advanced SFR burner cores using new blanket fuels was assessed by evaluating the bare critical mass (BCM), the spontaneous fission neutron source (SNS) rate, and thermal heat generation (TG) rate for the unit mass of the plutonium and the uranium proliferation index of the discharged fuel. The BCMs were evaluated by using MCNP6 [9] for a bare sphere. The SNSs and TGs values were calculated by using ORIGEN-2 [10] and the plutonium compositions evaluated with REBUS-3. We searched the contents of DU and TRU in thorium blanket to satisfy the uranium(U) proliferation index and to have comparable values of the other proliferation parameters of plutonium (50MWD/kg and zero years cooling). The result of search showed that the new blanket of 65wt%Th-30wt%DU-5wt%TRU satisfies the uranium proliferation index and has the comparable parameters of proliferation resistance to the reference PWR spent fuel. For DU blanket, we searched the contents of TRU which leads to the comparable proliferation resistance parameters to those of the LWR spent fuel. The search showed that 10% TRU addition is required for the purpose. The proliferation resistance parameters for new blankets were evaluated after analyzing the performances of the burner cores having new blankets and the results are summarized in Table III.

Table II Comparison of the core performances of cores having thorium or depleted uranium blankets from the uranium-free SFR burner cores

Design parameter Fuel blanket type	Reference N/A	Case T Th-10Zr	Cast T-M Th-10Zr	Case D DU-10Zr	Case D-M DU-10Zr
Number of $ZrH_{1.8}$ moderator rods	N/A	N/A	12	N/A	12
Burnup reactivity swing (pcm)	5485	3898	3159	3685	3090
Average discharge burn-up(MWD/kg)	182	140	136	124	122
Driver		181	170	179	168
Blanket		25	33	21.6	26.5
Inventory (kg,BOEC/EOEC)					
TRU (Driver)	6578 / 6227	6294 / 5961	6801 / 6470	6263 / 5935	6611 / 6288
TRU (Blanket)				83/133	78/122
^{232}Th or ^{238}U (Blanket)		2423 / 2370	2300 / 2244	3576 / 3507	3404 / 3336
W	11393 / 11393	7975 / 7975	6888 / 6888	8014 / 8014	6956 / 6956
Total HM (Driver + Blanket)	6578 / 6227	8902 / 8551	9165 / 8815	10051 / 9701	10230 / 9880
TRU support ratio	3.757	3.572	3.531	3.512	3.475
Average linear power (W/cm)	190.6	190.6	200.1	190.6	200.1
Peaking linear power (W/cm)	294	332	354	330.9	343
Fuel Doppler coefficient (pcm/K, 890K)	-0.177	-0.218	-0.580	-0.295	-0.559
Sodium void worth (pcm)	2371	2213	1615	2358	1718

Table III Comparison of proliferation resistance of discharged axial different blankets

Design parameter Fuel blanket type	Case NT-1 65Th-30DU-5TRU	Case NT-2 65Th-30DU-5TRU	Case ND-1 90DU-10TRU	Case ND-2 90DU-10TRU	Case [a]PWR N/A
Number of $ZrH_{1.8}$ moderator rods	12	12	12	12	N/A
The use of recycling option(Blanket)	No	Yes	No	Yes	N/A
Average discharge burnup(MWD/kg)	40.2	47.9	48.0	70.3	50.0
[b]U proliferation index(%)(<12%)	11.63	11.49	0.01	0.01	0.5
Plutonium contents wt%(100%)					
Pu-238	3.7	3.0	3.7	2.4	2.7
Pu-239	63.0	51.3	62.7	50.4	58.8
Pu-240	23.7	33.4	24.0	34.4	14.9
Pu-241	4.8	6.1	5.3	7.2	16.2
Pu-242	4.8	6.2	4.4	5.5	7.3
BCM(kg)	13.14	14.97	13.28	15.06	12.98
		Spontaneous fission neutron source $(kg\text{-}sec)^{-1}$			
Pu-238	$99x10^3$	80	99	64	$73x10^3$
Pu-240	$216x10^3$	304	218	313	$136x10^3$
Pu-242	$80x10^3$	104	73	93	$124x10^3$
Total SNS /kg of Pu	$395x10^3$	488	390	470	$332x10^3$
		Thermal heat generation (watt/kg of Pu)			
Pu-238	21.16	17.27	21.05	13.59	15.59
Pu-239	1.21	0.98	1.20	0.97	1.13
Pu-240	1.68	2.37	1.70	2.44	1.06
Pu-241	0.15	0.20	0.17	0.23	0.52
Pu-242	0.01	0.01	0.00	0.01	0.01
Total TG /kg of Pu	24.24	20.83	24.13	17.24	18.30

[a]U-235(4wt%), 50MWD/kg, and zero cooling time.

[b] $\text{U proliferation index} = \frac{^{233}U + 0.6\,^{235}U}{U^{total}} \times 100 < 12\text{wt\%}$

Table IV Comparison of performances of the cores having axial different blankets

Design parameter Fuel blanket type	Case NT-1 65Th-30DU-5TRU	Case NT-2 65Th-30DU-5TRU	Case ND-1 90DU-10TRU	Case ND-2 90DU-10TRU
Number of $ZrH_{1.8}$ moderator rods	12	12	12	12
The use of recycling option(Blanket)	No	Yes	No	Yes
Burnup reactivity swing (pcm)	3313	3409	3569	3862
Average discharge burn-up(MWD/kg)	133.7	135.2	126	132
Driver	168.8	168.4	166	165
Blanket	40.2	47.9	48.0	70.3
HM inventory(BOEC/EOEC, kg)	9320 / 8969	9211 / 8860	9871 / 9521	9447 / 9097
Driver	6666 / 6343	6566 / 6248	6412 / 6106	6023 / 5738
Blanket	2655 / 2626	2645 / 2611	3459 / 3415	3424 / 3359
TRU inventory(BOEC/EOEC, kg)	6682 / 6365	6668 / 6350	6674 /6390	6557 / 6267
Driver	6537 / 6216	6438 / 6123	6286 / 5982	5904 / 5621
Blanket	145 / 149	230 / 227	389 / 408	653 / 646
TRU support ratio	3.443	3.417	3.262	3.112
Peaking linear power (W/cm)	342	340	337	327
Fuel Doppler coefficient (pcm/K, 890K)	-0.536	-0.544	-0.563	-0.583
Radial expansion coefficient (pcm/K)	-0.673	-0.663	-0.637	-0.627
Fuel axial expansion coefficient (pcm/K)				
Fuel only	-0.410	-0.411	-0.411	-0.408
Fuel+clad	-0.212	-0.212	-0.212	-0.210
Sodium density (pcm/K)	0.489	0.494	0.510	0.508
Sodium void worth (pcm)	1708	1714	1747	1716
$A/B \le 1$	1.016	1.035	1.084	1.104
$1 \le C\Delta T_C / B \le 2$	1.254	1.258	1.267	1.278
$\Delta\rho_{TOP} / \lvert B \rvert \le 1$	0.880	0.913	0.982	1.065

As shown in Table III, the discharged thorium based blanket of 65wt%Th-30wt%DU-5wt%TRU has an uranium proliferation index of 11.63wt% lower than the limiting value of 12wt% and a similar fissile Pu contents than that of the LWR spent fuel (50MWD/kg and zero cooling time). This blanket also has 13.14 kg BCM, $395x10^3$ $kg\text{-}sec^{-1}$ SNS, and 24.24 watt/kg TG witch are higher than those of the reference PWR spent fuel. It means that the plutonium of this blanket has higher proliferation resistance than the reference PWR spent fuel. With recycling, this discharged thorium-based blanket has a slightly reduced U proliferation index, a larger values of BCM and SNS, and a reduced TG in comparison with one without recycling but they are still higher than those of the reference PWR spent fuel. The discharged uranium-based blanket of 90wt%DU-10wt%TRU also has higher values of the proliferation resistance parameters than those of the reference PWR spent fuel and they are similar to those of the previous thorium-based blanket (i.e., 65wt%Th-30wt%DU-5wt%TRU). But it is noted that the TG value of this blanket with recycling is slightly smaller due to its lower ^{238}Pu content than that of the reference PWR spent fuel. The performances of the cores having different new blankets are compared in Table IV. In Table IV, it is shown that the core having new thorium-based blanket has a slightly reduced TRU support ratio of 3.44, a slightly larger burnup reactivity swing by 154pcm , a slightly less negative Doppler coefficient and slightly higher sodium void worth than the core having the original thorium blanket. The use of recycling option leads to an increase of the initial fissile inventory which gives a small degradation of TRU support ratio and a slight increase of burnup reactivity swing by 94pcm. Also, the use of blanket with recycling option leads to only small changes of peak linear power density and reactivity coefficients in comparison with the core having the blankets with no recycling option. These trends are mainly due to the reduction of the TRU contents in the driver fuels, which is resulted from the higher fission contributions by new blankets. These trends are very similar to the DU-based blanket. Finally, we performed the quasi-static reactivity balance analysis [11] to check if the cores have passive self-controllability under ATWS (anticipated transients without scram). This self-controllability can be used as a measure of the inherent safety features of the cores. From Wade and Hill, it was shown that the self-controllability for a sodium cooled fast reactor is satisfied if the three criterions are met (see Table IV). In Table IV, it was shown that all the cores satisfy all the criterions for the self-controllability. However, the core having new depleted uranium based blanket with recycling option does not satisfy the last criterion associated with UTOP, which is due to the large burnup reactivity swing of this core because of high breeding effect of fissile actinides in the new depleted uranium based blankets.

3. Conclusions

In this paper, a comparative design study of advanced sodium uranium-free fueled cooled burner cores having thorium or depleted uranium based blankets was done to analyze their relative neutronic features. The analysis results showed that the cores using thorium or depleted uranium based blankets have significantly lower burnup reactivity swing, more negative Doppler coefficients and lower sodium void reactivity than their corresponding cores having no blanket. In addition, we considered new blankets by adding DU and TRU to consider the proliferation resistance. The use of new blankets led to slightly degraded performance such as burnup reactivity swing, sodium void reactivity, and TRU burning rate in comparison with the use of the blanket. However, they still have high TRU support ratio of 3.1~3.4 even if a recycling option for each blanket are considered. Also, it was shown that the cores having new blankets have higher proliferation resistance parameters than the reference PWR spent fuel. However, the DU-based blankets with recycling option have lower TG rates than that of the LWR spent fuel of 50MWD/kg due to the low ^{238}Pu contents. Finally, the quasi-static reactivity balance analysis results showed that all the cores satisfy all the criterions for the self-controllability except for the core having the DU-based blanket with recycling option.

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