An Option Study of Sodium-Cooled Burner Cores having Uranium-Free Metallic Fuels

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1. Introduction

One of the obstacles for sustainable energy supply using nuclear power plants is the safe and effective management of nuclear spent fuel because the reduction of the radiotoxicity down to the natural toxicity level (i.e., the equilibrium toxicity level of the natural uranium required for LWF fuel fabrication) takes a few hundred-thousand years. However, it is known that the separation of plutonium and uranium from LWR spent fuel reduces the radiotoxicity of the remaining HLW (High Level Waste) in the time frame from 10^3 to 10^5 years by an order of magnitude and that the fast spectrum reactors can use effectively these actinides and recycle them[1,2].

In particular, the SFR (Sodium-cooled Fast Reactor) can be designed to effectively incinerate TRU (Transuranic) nuclides coupled with recycling of actinides. However, the typical SFR burners have a limited ability of TRU burning rate because they use the fuels containing fertile nuclides such as ^{238}U and ^{232}Th and these fertile nuclides generate high mass actinides through neutron capture. So, the maximization of the TRU burning rate requires the removal of the fertile nuclides from the fuels is required. However, it has been well-known that the removals of the fertile nuclides from the fuel degrade the inherent safety of the SFR burner cores through the significant decrease of the fuel Doppler effect, increase of burnup reactivity swing, and reduction of delayed neutron fraction.

In this work, 400MWe SFR burner cores using metallic fertile-free fuels [3] are designed and analyzed in view point of the core physics. In particular, we considered two different options for enhancing core performances : 1) The first option uses the axially central B_4C absorber regions in the fuel rods to reduce burnup reactivity swing and sodium void worth and 2) The second option uses the axially central thorium blanket region for the same purpose.

2. Computational Method and Models

The REBUS-3 equilibrium model [4] 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 core physics parameters were evaluated with 80 group cross section and DIF3D HEX-Z nodal option [5]. These multi-group cross sections were produced with the TRANSX code [6] and an ENDF/B-VI.r6. 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. The composition of external TRU feeding corresponds to the TRU composition of LWR spent fuel having discharge burnup of 50MWd/kg and 10 years cooling.

3. Core Design and Performance Analysis

3.1 Description of the Core Designs

The cores considered rate 400MWe (1015.6). The configuration is shown in Fig. 1. As given in our previous works [7,8,9], the core consists of two different type fuel assemblies that were devised to achieve power flattening with a single feed fuel composition. The normal fuel assemblies comprised of 271 fuel pins within a normal duct of 3.7mm thick are loaded in the outer region while the thick duct fuel assemblies having 217 fuel pins are in the inner core. The reactivity control system consists of two separate control rod groups (i.e., primary and secondary groups comprised of 31 and 6 control rod assemblies, respectively). A large number of primary control rod assemblies were considered to cope with the large burnup reactivity swing that may be expected in the burner cores. The ternary metallic fuels of TRU-Ni-10Zr and TRU-W-10Zr are considered to improve the Doppler coefficient by adding resonant nuclides. Table I summarizes the main design parameters of the cores. Fig. 2 shows the R-Z cut view of the core. In this work, two different options for the insertion of axial heterogeneity are considered and inter-compared.

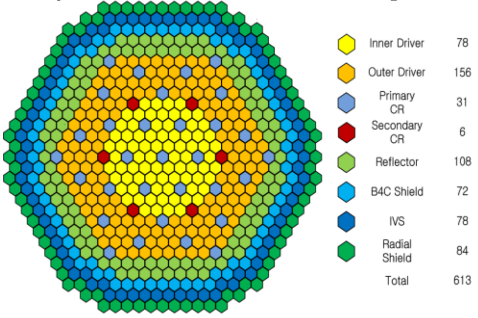

Fig. 1. Radial configuration of the cores

Table I: Main design parameters of the cores

Design parameter	Specification
Power (MWe/MWt)	400/1015.6
Fuel type(Ternary metal alloy)	TRU-W(or Ni)-10Zr
Number of rods per FA	[a]271 /217
Smear density of fuel	75%
Duct wall thickness(mm)	[a]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	4
Core active height(cm, cold)	90
Volume fraction(fuel/coolant/structure)	
Inner core	30.6/30.8/38.6
Outer core	38.3/36.9/24.8

[a] Values for the normal and new assemblies, respectively

The axial B_4C region is introduced to reduce the burnup reactivity swing by increasing heavy metal loading and to reduce sodium void worth by increasing neutron absorption under sodium voiding while the thorium blanket to reduce burnup reactivity swing and to increase the Doppler effects by partially adding the fertile resonant nuclide. The heights of the axially central heterogeneity regions were selected to be 18cm. The absorber material in the absorber region is boron carbide whose B-10 content is 20.0wt%. The average linear heat generation rate of the reference core having thorium blanket is 175.0 W/cm and it is increased to 218 W/cm for the cores having the absorber region. All the cores considered in this work use the same four batch refueling scheme and the same cycle length of 332 EFPDs.

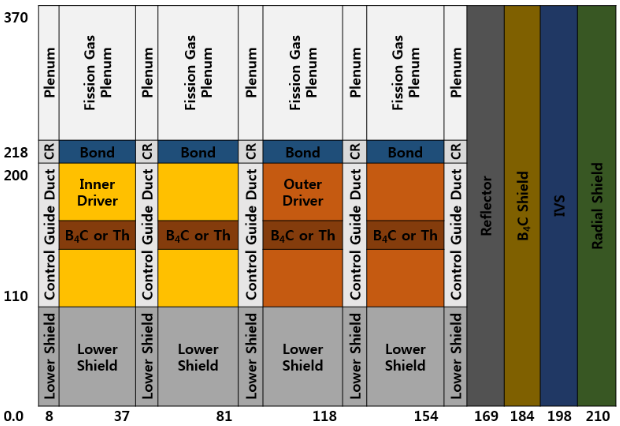

Fig. 2. Axial configuration of the cores having absorber region or thorium blanket

3.2 Core Performance Analysis

First, we analyzed the core performance parameters and inter-compared of the six different cores having different design options. The first case denoted as Case N is the reference core which uses TRU-Ni-10Zr fuel but does not axial absorber and thorium blanket. The second core (Case N-B) uses the same nickel-based fuel but it uses axial B_4C region while the third core (Case N-T) uses the nickel-based fuel and axial thorium blanket. The remaining three cores (Case W, Case W-B, Case W-T) correspond to the Cases N, N-B, and N-T, respectively, but they use TRU-W-10Zr fuel. Table II summarizes the performances of these cores.

Table II: Comparison of the performances of the cores loaded with fertile-free fuels

Design parameter	Case N	Case N-B	Case N-T	Case W	Case W-B	Case W-T
Fuel driver type		TRU-Ni-10Zr			TRU-W-10Zr	
B_4C absorber thickness (cm, cold)	N/A	18	N/A	N/A	18	N/A
Th-blanket thickness (cm, cold)	N/A	N/A	18	N/A	N/A	18
Average linear power (W/cm)	175	218	175	175	218	175
Burnup reactivity swing (pcm)	6740	4475	4352	5606	4140	3999
Average discharge burnup (MWD/kg)	240	184	163	256	165	146
TRU support ratio	3.72	3.73	3.49	3.70	3.75	3.56
Cycle average TRU conversion ratio	0.44	0.36	0.42	0.43	0.36	0.40
TRU consumption rate (kg/cycle)	351	351	329	354	354	336
Fuel inventories (kg, BOEC/EOEC)						
TRU	4833/4485	6591/6240	4902/4575	6162/5812	7436/7084	5901/5568
Ni, or W	7124/7124	2928/2928	4562/4562	11801/11801	6931/6931	8362/8362
Th	N/A	N/A	2410/2350	N/A	N/A	2422/2369
TRU contents in Fuel (wt%, BOEC/EOEC)	36.0/34.3	69.0/68.2	45.1/43.4	30.6/29.3	51.8/50.5	29.3/28.1
[a]Peak linear power density (W/cm)	275	428	305	273	440	309
Fast neutron fluence (n/cm^2)	2.97x10^{23}	2.46x10^{23}	2.76 x10^{23}	2.60x10^{23}	2.32x10^{23}	2.43 x10^{23}
[a,b]Fuel Doppler coefficient (pcm/K)	-0.0887	-0.0249	-0.2103	-0.1894	-0.0738	-0.231
[a]Radial expansion coefficient (pcm/K)	-0.823	-1.07	-0.868	-0.761	-1.01	-0.819
[a]Fuel axial expansion coefficient (pcm/K)	-0.339	-0.39	-0.35	-0.368	-0.37	-0.369
[a]Sodium void worth (pcm)	1419 (5.5$)	1033 (4.5$)	1516	2276 (9.6$)	1230 (5.6$)	2131
[a]Primary control rod worth (pcm)	16578	8918	15870	13004	7771	13076
[a]Secondary control rod worth (pcm)	4411	2492	4303	3516	2186	3608
[a]Effective delayed neutron fraction	0.00260	0.00228		0.00237	0.00221	

[a] Values at BOEC, [b] At 900K

As shown in Table II, the uses of the axial B_4C absorber and thorium blanket significantly reduce the burnup reactivity swing by 2265 and 2388pcm, respectively, than the reference case using the nickel-based fuel and these reductions of burnup reactivity swings are also observed for the cores using tungsten-based fuel. These reductions of the burnup reactivity swings for the cores using axial heterogeneity are due to the lower discharge burnup resulted from the larger heavy metal inventories than the reference cores. In particular, the cores using axial thorium blanket have lower discharge burnup by ~13% than the corresponding cores having B_4C absorber region due to the additional thorium inventory. All the cores have very high TRU support ratio larger than 3.49 and their differences in TRU support ratios are very small because they used fertile-free fuels. This fact means that these cores can consume the amount of TRUs discharged from 3.49~3.75 PWRs of the same thermal power and cycle length. The smaller TRU support ratios of the cores having axial thorium blanket are due to the fissile nuclide generation in the blanket. Also, it is shown in Table II that they have the similar TRU burning rates of 329~354kg/cycle. The cores having axial B4C region have higher TRU contents in fuel than the other cores due to the strong neutron absorption by B_4C. One of the advantages for the axial thorium blanket core is its much lower peak power density than the corresponding core having axial B_4C region because the thorium blanket generates small fission power. Also, it is noted that the thorium blanket cores have significantly more negative Doppler effects, higher control rod worth but larger sodium void worth than the corresponding cores having B_4C region. The nickel-based fueled cores have less negative Doppler coefficients but smaller sodium void worth than the corresponding tungsten-based fueled cores. The difference in the sodium void worth is larger for the thorium blanket cores than for the cores having axial B_4C region.

Next, we considered addition of six moderator ($ZrH_{1.8}$) rods to improve the Doppler coefficient and to reduce the sodium void worth by neutron spectrum softening. Table III summarizes the results of the performance analysis for these cores. In Table III, the cores having six moderator rods per each fuel assembly are denoted by just adding '-M' to their corresponding cores having no moderators. The comparison of Tables II and III shows that as expected the new cores having moderator rods have more negative Doppler coefficients and the absolute values of the Doppler coefficients are nearly doubled. Also, it is noted that the new cores having moderator rods have smaller burnup reactivity swings and specifically thorium blanket fueled cores have more reduced burnup reactivity swings with moderators. For example, the cores having moderators have smaller burnup reactivity swing by 504pcm and 468 pcm than the corresponding cores without moderators for the nickel- and tungsten-based fuels. Also, as expected, the cores having moderator rods have smaller sodium void worth than their corresponding cores having no moderators.

Table III: Comparison of the performances of the cores having moderator rods

Design parameter	Case N-B-M	Case N-T-M	Case W-B-M	Case W-T-M
Fuel driver type	TRU-Ni-10Zr		TRU-W-10Zr	
B_4C absorber thickness (cm, cold)	18	N/A	18	N/A
Th-blanket thickness (cm, cold)	N/A	18	N/A	18
Number of moderator rods	6	6	6	6
Average linear power (W/cm)	224	181	224	181
Burnup reactivity swing (pcm)	4355	3848	4034	3531
Average discharge burnup (MWD/kg)	182	164	162	143
TRU support ratio	3.73	3.45	3.75	3.54
Cycle average TRU conversion ratio	0.39	0.45	0.38	0.42
TRU consumption rate (kg/cycle)	352	326	353	334
Fuel inventories (kg, BOEC/EOEC)				
TRU	6670/6320	4960/4637	7589/7237	6239/5909
Ni, or W	2609/2609	4272/4272	6424/6424	7804/7804
Th	N/A	2348/2286	N/A	2360/2305
TRU contents in Fuel (wt%, BOEC/EOEC)	71.8/70.7	36.9/35.4	54.2/53.0	30.3/29.1
Peak linear power density (W/cm)	442	313	455	316
Fast neutron fluence (n/cm^2)	$2.27x10^{23}$	$2.38\ x10^{23}$	$2.14x10^{23}$	$2.15\ x10^{23}$
Fuel Doppler coefficient(pcm/K,900K, BOEC)	-0.0583	-0.4300	-0.1305	-0.4275
Radial expansion coefficient (pcm/K, BOEC)	-1.03	-0.789	-0.964	-0.744
Fuel axial expansion coefficient (pcm/K, BOEC)				
Fuel only	-0.372	-0.327	-0.370	-0.389
Sodium void worth (pcm, BOEC)	811(3.5$)	1229	1054(4.7$)	1789
Control rod worth (pcm, BOEC)				
Primary	8429	14325	7245	11572
Secondary	2340	3856	2026	3177
Effective delayed neutron fraction (BOEC)	0.00231		0.00224	

For example, the new nickel-based fueled core having axial B_4C region and moderator rods has the smallest sodium void worth of 3.5$. On the other hand, these new cores using moderator rods have reduced control rod worth due to the increased neutron absorption in the axial B_4C region and in the thorium blanket region.

4. Summary and Conclusions

In this work, we performed comparative core physics analysis of the new advanced SFR burner cores loaded with uranium-free fuels to maximizing TRU burning rate. Two resonant nuclides (i.e., nickel and tungsten) were considered to be added into the uranium-free metallic fuels for improving the Doppler coefficient. In particular, the main point of this work is to inter-compare two different options for introducing axial heterogeneity in order to improve the core performances. The first option is to locate the axially central B_4C absorber region and the second one to locate the axially central thorium blanket. The analysis results showed that these new cores significantly reduces the burnup reactivity swing which is one of the problems in the cores loaded with uranium-free fuels, and also these cores have significantly improved Doppler coefficient and sodium void worth with the six $ZrH_{1.8}$ moderator rod per one fuel assembly. Specifically, it was found from this study that the cores having axial thorium blanket has more negative Doppler coefficient with slightly reduced TRU burning rate, flatter power distribution, and larger control rod worth than the cores having axial B_4C absorber region while the cores having axial B_4C region has smaller sodium void worth due to its increased neutron absorption in the B_4C region under sodium voiding.

Acknowlegement

This work was supported from National Research Foundation (NRF) of Korea through project No. NRF-2015M2A8A6010482

REFERENCES

[1] J. Tommasi, M. Delpech, J. P. Grouiller, and A. Zaetta, “Long-lived Waste Transmutation in Reactors,” Nuclear Technology, Vol.111, p.133 (1995).

[2] M. Salvatores, “Transmutation : Issues, Innovative Options and Perspectives,” *Progress in Nuclear Energy*, Vol.40, p.375 (2002).

[3] A. Romano, P. Hejzlar, N. E. Todreas, “Fertile-Free Fast Lead-Cooled Incinerators for Efficient Actinide Burning, Nuclear Technology, Vol.147, p.368 (2004)

[4] B. J. Toppel, “A User’s Guide to the REBUS-3 Fuel Cycle Analysis Capability,” ANL-83-2, Argonne National Laboratory (1983).

[5] K. D. Derstine, “DIF3D : A Code to Solve One-, Two-, and Three-Dimensional Finite Difference Diffusion Theory Problems,” ANL-82-64, Argonne National Laboratory (Apr. 1984).

[6] R.E. MacFarlane, “ TRANSX 2: A Code for Interfacing MATXS Cross Section Libraries to Nuclear Transport Codes,”LA-12312-MS, Los Alamos National Laboratory (2013).

[7]W. You and S. G. Hong, “A Neutronic Study on Advanced Sodium Cooled Fast Reactor Cores with Thorium Blankets for Effective Burning of Transuranic Nuclides,” Nuclear Engineering and Design, Vol.278, p.274 (2014).

[8] W. You and S. G. Hong, “Sodium-cooled Fast Reactor Cores using Uranium-Free metallic Fuels for maximizing TRU Support Ratio,” Transactions of the Korean Nuclear Society Autumn Meeting, Pyeongchang, Korea, 2014 October 30-31.

[9] W. You and S. G. Hong, “An Advanced Option for Sodium Cooled TRU Burner Loaded with Uranium-Free Fuels,” Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, 2015 May 7-8.