A Consistent Comparative Study of Advanced Sodium-cooled Fast Burner Cores loaded with Thorium and Uranium-based Metallic Fuels

WuSeung You and Ser Gi Hong*
Dep. Of Nuclear Enginnering, Kyung Hee University, 1732 Deokyoungdaero, Giheung-gu, Yongin, Gyeonggi-do, 446-701
**Corresponding author: sergihong@khu.ac.kr*

I. Introduction

Recently, we have studied 400MWe advanced sodium cooled reactor cores[1] using thorium blanket for improving the core performances including burnup reactivity swing, TRU burning rate, and sodium void worth. In our previous studies[2,3], we considered uranium-based metallic fuel of TRU-U-10Zr for driver fuel and thorium was considered as blanket because thorium blanket produces less amount of TRU than uranium blanket and use of thorium blanket leads to smaller sodium void worth than the use of uranium blanket due to the fact that the η-value increases much less with energy for ^{233}U than for ^{239}Pu and ^{232}Th is less fissile than ^{238}U. However, these cores using thorium blanket still have a large amount of TRU production from the driver fuels because the driver fuels contain a large amount of depleted uranium which leads to the production of TRU through neutron capture.

The objective of this work is to consistently compare the neutronic performances of advanced sodium cooled fast reactor cores loaded with thorium and uranium-based metallic fuels as driver fuel for TRU burning. Our main emphasis is given on the analyses of the differences in the core performance parameters. For consistent comparison, we used the same core configuration and all the same design parameters except for the fact that depleted uranium in uranium-based fuel is replaced with thorium. We considered the cores having no thorium blanket and the cores having thorium blanket that were designed in our previous works. The computational methods and models are briefly given in Sec. II and Sec. III gives the detailed core design study and core performance analyses. Finally, the summary and conclusions are given in Sec. IV.

II. Computational Methods 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) are 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[5]. The 150 group cross section library of ISOTXS format is generated using TRANSX code[6] 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. The decay chain spans the range from ^{232}Th to ^{246}Cm. We assumed 99.1% 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. In our work, it was assumed that 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.

III. Core Design Study and Performance Analysis

III.A. Reference Configuration Cores

A reference core configuration is shown in Fig. 1. This reference core configuration is from our previous studies and this reference core configuration has no thorium blanket. All cores considered in our work rate 1015.6MWt (400MWe). As shown in Fig. 1, the core consists of two radial regions (i.e., inner and outer regions) that have different fuel assemblies.

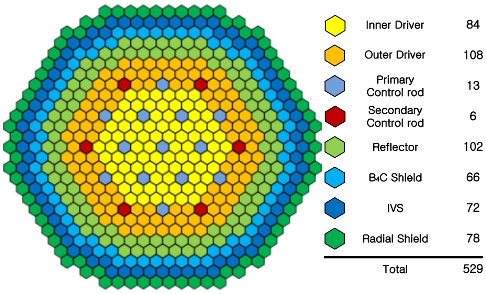

Fig. 1. Reference core configuration

The outer core region is comprised of the normal hexagonal fuel assemblies which consist of 271 fuel pins (i.e., 10 hexagonal rings of fuel pins) in a duct. On the other hand, a new fuel assembly design devised for improving TRU burning rate and for achieving power flattening with a single TRU content in charging fuel is used in the inner core region. This fuel assembly consist of 217 fuel rods (9 hexagonal rings) while its duct is increased to keep the same assembly pitch as normal fuel assembly of 271 fuel rods. Table I summarizes main design parameters of the reference core. The outer diameter of fuel rod is 7.5mm and clad thickness is 0.53mm. The duct thickness for the normal and the thick duct assemblies are 3.7 and 11.5mm, respectively. The cycle length is 332 EFPD (Effective Full Power Days) and four fuel management scheme is used both for inner and outer core regions. The active core is 90cm high at cold state. The average linear heat generation rate is 220.0W/cm. For this reference core configuration, the performances of the cores loaded uranium-based (TRU-U-10Zr) and thorium-based (TRU-Th-10Zr) metallic fuels are analyzed and the results are given in Table II.

Table I Design parameters for the reference core configuration

Design parameter	Specification
Power (MWe/MWt)	400/1015.6
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
Average linear power density (W/cm)	220.0

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

Table II Comparison of performances of the reference configuration cores

Parameter	Case A-1	Case A-2
Driver fuel type	TRU-U-10Zr	TRU-Th-10Zr
Active core height (cm)	90	90
Burnup reactivity swing (pcm)	2239	3886
Average discharge burnup (MWD/kg)	89	114
TRU support ratio	0.97	1.94
Cycle average conversion ratio	0.84	0.64
Heavy metal inventories (kg)	[b]14118/13772	10989/10643
TRU inventories (kg, BOEC/Δ[a])	3194/-3	2613/-7
TRU consumption rate (kg/cycle)	91	183
Thorium inventories (kg,BOEC/Δ[a])	N/A	7304/-2.23
^{233}U inventories (kg, BOEC/Δ[a])	N/A	707/-0.6
Average linear power (W/cm)	220	220
Peak linear power density (W/cm)	[b]332/327	323/317
Fast neutron fluence (n/cm^2)	3.79x10^{23}	3.59x10^{23}

[a]Δ=(EOEC-BOEC)/BOECx100 (%),
[b]Values at BOEC and EOEC, respectively

As shown in Table II, the cores loaded uranium and thorium-based fuels are denoted by Case A-1 and Case A-2, respectively. From Table II, it is noted that the core loaded thorium-based fuel has much higher TRU consumption rate by ~100% and higher burnup reactivity swing by ~1647pcm than the core loaded with uranium-based fuel. These big differences are due to the facts that ^{232}Th has higher absorption cross section than ^{238}U, the fertile nuclides produced from ^{232}Th have higher threshold energies for fission than those produced from ^{238}U, ^{232}Th has higher threshold energy for fission and smaller fission cross section than ^{238}U, ^{233}U has smaller η value than ^{239}Pu under fast neutron spectra. These features lead to the lower breeding characteristics of thorium-based fuel than uranium-based fuel. The replacement of uranium-based fuel with thorium-based fuel leads to the change of cycle average conversion ratio from 0.84 to 0.64. The higher discharge burnup of the core loaded with thorium-based fuel is due to the lower density of thorium-based fuel. Both of the cores have small peak linear power densities below a typical limiting value of 500W/cm. In Table III, the contents of major actinides in HM (Heavy Metal) are analyzed in detail. As shown in Table III, the core loaded with thorium-based fuel has much higher contents of fissile (^{233}U, ^{235}U) plus TRU nuclides than the core loaded with uranium-based fuel. The contents of ^{233}U are estimated to be 6.5wt% both at BOEC and EOEC for the core loaded with thorium-based fuel. Fig. 3 compares the consumption rate of TRU of the two cores. As shown in Fig. 3, the core loaded with thorium-based fuel has much higher consumption rates (kg/cycle) for all the TRU nuclides than the core loaded with uranium-based fuel.

Table III Comparison of the contents of major actinides for the reference configuration cores (wt%)

Nuclides	Case A-1	Case A-2
^{233}U	[a]0.0 / 0.0	[a]6.5 / 6.6
^{235}U	0.0 / 0.0	0.5 / 0.5
TRU	22.6 / 22.5	23.8 / 22.8
Total (Fissile + TRU)	22.7 / 22.6	30.8 / 30.0
^{232}Th	0.0 / 0.0	66.5 / 67.1
^{233}Pa	0.0 / 0.0	0.1 / 0.2
^{234}U	0.1 / 0.1	2.1 / 2.2
^{236}U	0.0 / 0.0	0.5 / 0.5
^{238}U	77.2 / 77.2	0.0 / 0.0

[a]Values for BOEC and EOEC, respectively

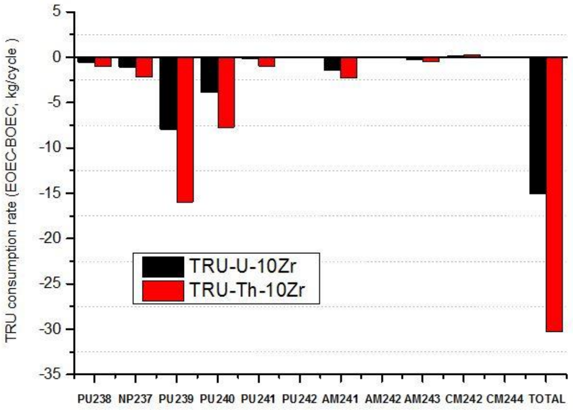

Fig. 3. Comparison of the consumption rates of TRU nuclides

The reactivity coefficients for the Cases A-1 and A-2 are compared in Table IV. Overall, both cores have comparable reactivity coefficients although the core loaded with thorium-based fuel has less negative values of the Doppler, radial expansion, and axial expansion reactivity coefficients than the core loaded with uranium-based fuel. The less negative Doppler coefficient is due to the higher fissile contents in the Case A-2 core than the Case A-1 core. In particular, it should be noted that the Case A-2 core loaded with thorium-based fuel has much smaller sodium void worth and correspondingly much smaller value of coolant expansion reactivity coefficient than the Case A-1 core. The improved coolant expansion reactivity coefficient can offset the degradation of the other reactivity coefficients. The much low sodium void worth is related to the higher fission threshold energy and lower fission cross section of ^{232}Th than ^{238}U, and the fact that the fission cross section of ^{233}U decreases as energy while the one of ^{239}Pu is almost constant . In SFR, core voiding may happen during accidents leading to sodium boiling such as UTOP (Unprotected Transient OverPower) and ULOF (Unprotected Loss of Flow) and it may exacerbate the consequences of the accidents. So, the low sodium void worth and coolant expansion reactivity coefficients are very helpful to mitigate these kinds of accident.

Table IV Comparison of the reactivity coefficients of the reference configuration cores (BOEC)

Parameter	Case A-1	Case A-2
Fuel Doppler coefficient (pcm/K, 900K)	-0.442	-0.338
Radial expansion coefficient (pcm/K)	-0.807	-0.775
Fuel axial expansion coefficient (pcm/K)		
Fuel only	-0.399	-0.328
Fuel+clad	-0.258	-0.218
Coolant expansion coefficient (pcm/K)	0.521	0.186
Sodium void worth (pcm)	1748	691
Control rod worth (pcm)		
Primary	10317	11468
Secondary	2927	3157

III.B. Core Designs with Axial Thorium Blankets

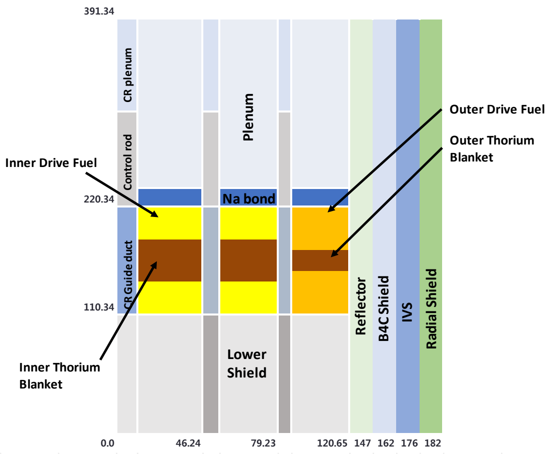

Fig. 4. RZ layout of the cores having axial thorium blankets

In this section, we considered the cores having axial thorium blanket that were designed in our previous study. The axial configuration of the cores is given in Fig. 4. As shown in Fig. 4, 50cm thick thorium blanket (Th-10Zr) is placed in the inner region while 35cm one is in the outer region. Figure 4 shows an axial cut view of the core having radially separated thorium blanket. In this work, we did not consider recycling of thorium blanket and so all of the blankets are discharged but not recycled. No recycling of blanket is to maximize breeding which leads to a large reduction of the burnup reactivity swing. The results of the detailed core performance analysis are summarized in Table V.

Table V Comparison of the core performances of cores having thorium blankets

Parameter	Case B-1	Case B-2
Driver fuel type	TRU-U-10Zr	TRU-Th-10Zr
Burnup reactivity swing (pcm)	2632	3082
Average discharge burnup (MWD/kg)		
Driver	148	186
Blanket	30	27
Driver+Blanket	106	114
TRU support ratio	2.53	2.95
Cycle average conversion ratio		
Driver	0.45	0.35
Blanket	2.83	2.98
Driver+Blanket	0.75	0.69
Heavy metal inventories (kg)	[b]11858/11510	11004/10656
TRU inventories (kg, BOEC/Δ[a])	3809/-6.2	3823/-7.2
TRU consumption rate (kg/cycle)	239	278
Thorium inventories (kg)		
Driver	[b]0/0	1721/1686
Blanket	[b]4221/4116	5037/4922
Driver+Blanket	[b]4221/4116	6758/6608
^{233}U inventories (kg, BOEC/Δ[a])		
Driver	[b]0/0	161/160
Blanket	[b]113/177	127/200
Driver+Blanket	[b]113/177	288/360
^{233}U contents in HM (wt%, Driver)	[b]0/0	2.76/2.90
^{233}U contents in HM (wt%, Blanket)	[b]2.61/4.10	2.46/3.88
Average linear power (W/cm)	220	220
Peak linear power density (W/cm)	[b]540/480	525/463
Fast neutron fluence (n/cm^2)	3.17x10^{23}	3.08x10^{23}

[a] Δ=(EOEC-BOEC)/BOECx100 (%),
[b] Values at BOEC and EOEC, respectively

The Case B-2 core loaded with thorium-based fuel has a smaller value of conversion ratio by 8% due to the inferior breeding characteristics of thorium-based fuel and it leads to a larger burnup reactivity swing by 450pcm and a larger TRU support ratio by 16.6% than the Case B-1 core loaded with uranium-based fuel. From these analyses, it is considered that the Case B-2 core has high TRU burning rate of 278kg/cycle with relatively small burnup reactivity swing and it can be considered as a good candidate burner core. When this core is compared with the Case A-1 core having no blanket, it is shown that this core has much higher TRU burning rate (i.e., TRU support ratio) but a much smaller burnup reactivity swing by 800pcm. Also, it is noted that the Case B-2 core has smaller peak linear power density than the Case B-1 core.

Table VI compares the contents of major actinides in HM. This table shows that the Case B-1 and B-2 cores have very high TRU contents larger than 50wt%, which is resulted from the low conversion ratio and that the Case B-2 core has smaller ^{233}U content in HM than the Case A-2 core.

Table VI Comparison of the contents of major actinides for the cores having thorium blankets (wt%)

Fuel contents in HM (wt% , BOEC/EOEC, Driver)	Case B-1	Case B-2
^{233}U	[a]0.0 / 0.0	[a]2.8 / 2.9
^{235}U	0.1 / 0.1	0.3 / 0.4
TRU	50.7 / 49.6	65.6 / 64.3
Total (Fissile + TRU)	50.8 / 49.8	68.7 / 67.6
^{232}Th	0.0 / 0.0	29.5 / 30.6
^{233}Pa	0.0 / 0.0	0.1 / 0.1
^{234}U	0.5 / 0.5	1.4 / 1.5
^{236}U	0.1 / 0.1	0.3 / 0.3
^{238}U	48.6 / 49.6	0.0 / 0.0

[a]Values for BOEC and EOEC, respectively

The reactivity coefficients including sodium void worth and control rod are compared in Table VII. Similarly to the trend shown in Sec. III.B, the Case B-2 core loaded with thorium-based fuel has less negative reactivity coefficients than the Case B-1 core loaded with uranium-based fuel. But the Case B-2 core has smaller coolant expansion reactivity coefficient and sodium void worth than the Case B-1 core. It is interesting to note that the Case B-2 core has larger sodium void worth by 225pcm than the Case A-2 while the Case B-1 core has smaller sodium void worth by 579pcm than the Case A-1 core. On the other hand, it is noted that the Case B-2 core has similar value of coolant expansion reactivity coefficient to that of the Case A-2 core. In this work, the sodium void worth was calculated by assuming that only flowing sodium coolants through the active fuel and the gas plenum regions are voided and so the sodium in the bond region above the fuel is not voided. The larger sodium void worth of the Case B-2 core than the Case A-2 core might be resulted from its higher TRU contents in fuel.

Table VII Reactivity coefficients of the cores having different fuel type with thorium blankets (BOEC)

Parameter	Case B-1	Case B-2
Fuel Doppler coefficient (pcm/K, 900K)	-0.319	-0.267
Radial expansion coefficient (pcm/K)	-0.973	-0.961
Fuel axial expansion coefficient(pcm/K)		
Fuel only	-0.366	-0.345
Fuel+clad	-0.262	-0.244
Coolant expansion coefficient (pcm/K)	0.267	0.187
Sodium void worth (pcm)	1169	926
Control rod worth (pcm)		
Primary	5874	6008
Secondary	3122	3130

III.C Annular Core Designs with no Thorium Blanket.

In this section, the annular core design having central non-fuel regions and no thorium blanket is considered. The configuration of the core is given in Fig. 5. The innermost four rings are comprised of B_4C shield assemblies and the next one ring is the sodium duct where sodium coolant is filled. These non-fuel regions in the central core region were used to enhance the TRU burning rate and to reduce sodium void worth by increasing neutron leakage through core.

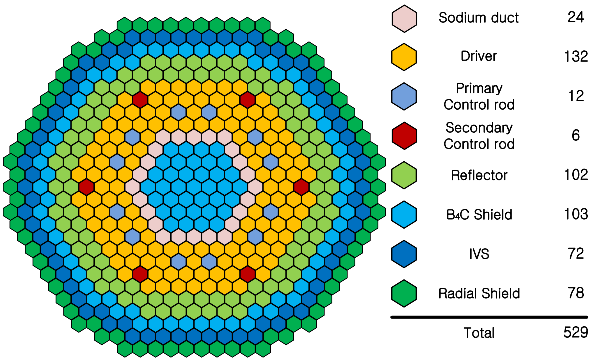

Fig. 5. Configuration of the core having central non-fuel regions

The active core height of this reference layout is 80cm and it rates 1015.6MWt (400MWe). The fuel rod and assembly design parameters are the same as those of the normal fuel assembly given in Table I. The fuel cycle length is 332EFPD and it uses a four batch fuel management scheme. The average linear heat generation rate is 328W/cm. The performances of the cores having uranium-based fuel (Case C-1) and thorium-based fuel (Case C-2) are summarized in Table VIII.

Table VIII Comparison of the core performances of annular cores having different fuel type

Parameter	Case C-1	Case C-2
Driver fuel type	TRU-U-10Zr	TRU-Th-10Zr
Active core height (cm)	80	80
Burnup reactivity swing (pcm)	4854	5883
Average discharge burnup (MWD/kg)	134	170
TRU support ratio	2.15	2.82
Cycle average conversion ratio	0.59	0.45
Heavy metal inventories (kg)	[b]9261/8912	7209/6861
TRU inventories (kg, BOEC/Δ[a])	3225/-6	3132/-8
TRU consumption rate (kg/cycle)	202	266
Thorium inventories (kg, BOEC/Δ[a])	-	3585/-2.31
^{233}U inventories (kg, BOEC/Δ[a])	-	326/-0.7
Average linear power (W/cm)	328	328
Peak linear power density (W/cm)	456/444	438/427
Fast neutron fluence (n/cm^2)	4.11x10^{23}	3.91x10^{23}

[a]Δ=(EOEC-BOEC)/BOECx100 (%),
[b]Values at BOEC and EOEC, respectively

As shown in Table VIII, both cores have large burnup reactivity swings due to their small conversion ratios and high discharge burnups. The Case C-2 core loaded with thorium-based fuel has larger burnup reactivity by 1029pcm and higher TRU support ratio by 31% than the Case C-1 core loaded with uranium-based fuel.

Table IX compares the reactivity coefficients of the cores having central non-fuel regions. As in the previous sections, the core loaded with thorium-based fuel has less negative reactivity coefficient except for the coolant expansion reactivity coefficient, much smaller sodium void worth than the core loaded with uranium-based fuel. In particular, it is noted that the Case C-2 core has negative sodium void worth and negative coolant expansion reactivity coefficient.

Table IX Comparison of the reactivity coefficients of the reference configuration cores (BOEC)

Parameter	Case C-1	Case C-2
Fuel Doppler coefficient (pcm/K, 900K)	-0.184	-0.132
Radial expansion coefficient (pcm/K)	-0.873	-0.866
Fuel axial expansion coefficient (pcm/K)		
Fuel only	-0.530	-0.492
Fuel+clad	-0.482	-0.470
Coolant expansion coefficient (pcm/K)	0.123	-0.083
Sodium void worth (pcm, BOEC/EOEC)	520	-113
Control rod worth (pcm)		
Primary	7327	7629
Secondary	2649	2845

Table X compares the contents of major actinides in heavy metals of fuel. As shown in this table, these cores have smaller contents of TRU and TRU plus fissile uranium (i.e., ^{233}U and ^{235}U) than the corresponding cores having thorium blankets considered in Sec. III.B. Also, the Case C-2 core has higher ^{233}U contents than the Case B-2 core. In the future, we will study the core designs having this configuration and thorium blankets to optimize the core performances such as burnup reactivity swing.

Table X Comparison of the contents of major actinides for the cores having thorium blankets (wt%) of the cores having central non-fuel regions

Fuel contents in HM (wt%, BOEC/EOEC)	Case C-1	Case C-2
^{233}U	0.0 / 0.0	4.5 / 4.7
^{235}U	0.1 / 0.1	0.4 / 0.4
TRU	34.8 / 33.9	43.5 / 41.8
Total (Fissile + TRU)	34.9 / 34.0	48.3 / 46.9
^{232}Th	0.0 / 0.0	49.7 / 51.0
^{233}Pa	0.0 / 0.0	0.1 / 0.1
^{234}U	0.2 / 0.2	1.5 / 1.6
^{236}U	0.1 / 0.1	0.3 / 0.3
^{238}U	64.8 / 65.7	0.0 / 0.0

IV. Summary and Conclusions

In this paper, a consistent comparative study of 400MWe advanced sodium cooled burner cores having uranium and thorium-based metallic fuels is done to analyze the relative core neutronic features. We considered three different core types : 1) annular type core having two different fuel assembly types, 2) same core type as the first type but having axial thorium blanket , and 3) annular type core having large central non-fuel region without thorium blankets. The results of the study showed that for all the core configurations, the core loaded with thorium-based fuel has higher TRU burning rate, smaller sodium void worth, and slightly less negative reactivity coefficients except for the coolant expansion reactivity coefficient than the corresponding core loaded with uranium-based fuel. For the annular type configuration having no thorium blanket, the core loaded with thorium-based fuel showed much higher burnup reactivity swing by ~1647pcm, much higher TRU burning rate by 100%, and much smaller sodium void worth by 60% than the corresponding uranium-based fuelled core. Also, it was found that the use of axial thorium blanket is still very effective in reducing burnup reactivity swing and increasing TRU burning rate for the thorium-based fuelled core but it is not effective in reducing sodium void worth as in the uranium-based fuelled core. For the annular core having large central non-fuel region and no blanket, it was shown that the thorium-based fuelled core has 31% higher TRU burnup rate, 21% larger burnup reactivity swing than the uranium-based fuelled core and that this thorium-based fuelled core has negative sodium void worth. However, both cores have very high burnup reactivity swing and we are planning to analyze the effectiveness of thorium blanket in the annular type core having large central non-fuel regions.

REFERENCES

[1] S. G. Hong, S. J. Kim, and Y. I. Kim, “Annular Fast Reactor Cores with Low Sodium Void Worth for TRU burning”, Nuclear Technology, Vol.162, p.1-25(2008)

[2] D. Y. Kim, H. L. Hyun, W. S. You, and S. G. Hong, “Performance Analysis of 400MWe Sodium Cooled Fast Reactor Cores Using Thick Duct Assembly for TRU Burning”, Transactions of the Korean Nuclear Society Autumn Meeting, Gyeongju, Korea, 2013 October 23-25.

[3] W. S. You, D. Y. Kim, H. L. Hyun, and S. G. Hong, “Sodium-cooled Fast Reactor Core Designs for TRU Burning with Thorium Blanket” Transactions of the Korean Nuclear Society Autumn Meeting, Gyeongju, Korea, 2013 October 23-25.

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

[5] R. E. Alcouffe et al., “User’s Guide for TWODANT: A Code Package for Two-Dimensional, Diffusion-Accelerated Neutral Particle Transport,” LA-10049-M, Los Alamos National Laboratory(1990).

[6] R. E. MacFralane, “TRANSX2: A Code for Interfacing MATXS Cross Section Libraries to Nuclear Transport Codes,”LA-12312-MS,Los Alamos National Laboratory (1992).