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Advanced Small-Safe Long-Life Lead Cooled Reactor Cores for Future Nuclear Energy

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1. Introduction

Fast reactors cooled by lead or lead-bismuth alloy have their promising features such as proliferation-resistance and superb safety, particularly for the small power reactors having long life[1,2]. These features are resulted from the thermal-hydraulic, chemical, and neutronic properties of these heavy liquid metal coolants. One of the reasons for use of the lead or lead-bismuth alloy coolants is the high boiling temperature that avoids the possibility of coolant voiding. Also, these coolants are compatible with air, steam, and water. Therefore, intermediate coolant loop is not required as in the sodium cooled reactors[3]. But the main drawback of the lead-bismuth alloy coolant is the radioactivity due to the alpha-emitter ^{210}Po. Lead is considered to be more attractive coolant than lead-bismuth alloy because of its higher availability, lower price, and much lower amount of polonium activity by factor of 10^4 relatively to lead. On the other hand, lead has higher melting temperature of 601K than that of lead-bismuth (398K), which narrows the operating temperature range and also leads to the possibility of freezing and blockage in fresh cores. Neutronically, the lead and lead-bismuth have very similar characteristics to each other. The lead-alloy coolants have lower moderating power and higher scattering without increasing moderation for neutrons below 0.5MeV, which reduces the leakage of the neutrons through the core and provides an excellent reflecting capability for neutrons. Due to the above features of lead or lead-alloy coolants, there have been lots of studies on the small lead cooled core designs.

In this paper, small-safe long-life lead cooled reactor cores having high discharge burnup are designed and neutronically analyzed. The cores considered in this work rates 110MWt (36.7MWe). In this work, the long-life with high discharge burnup was achieved by using thorium or depleted uranium blanket loaded in the central region of the core. Also, we considered a reference core having no blanket for the comparison. This paper provides the detailed neutronic analyses for these small long-life cores and the detailed analyses of the reactivity coefficients and the composition changes in blankets. The results of the core design and analyses show that our small long-life cores can be operated without refueling over their long-lives longer than 45EFPYs (Effective Full Power Year).

2. Methods and Results

2.1 Core Design Descriptions

The main design parameters are summarized in Table I. The core rates 110MWt (36.7MWe). The ternary metallic fuels of TRU-U-10Zr where uranium is the depleted uranium are considered as driver fuel to be loaded in the cores. The TRU (Transuranics) composition is from the composition of LWR spent fuel having 50MWD/kg and 10 years cooling. The enrichments of uranium are determined so as to achieve the initial criticality with a small excess reactivity (i.e., initial multiplication factor was set to 1.007). At present, the depleted uranium (DU) of U-10Zr and thorium (Th-10Zr) are alternatively considered as blanket. Also, we considered a long-life core having no blankets. The active fuel length including blanket is 165cm and the average heat generation rate for all the cases is 108W/cm. We adopted lower power density and blankets to achieve long-life core and high thermal margin. The thick fuel rods of 1.30cm diameter are adopted to have high volume fraction in order to achieve long-life core having high average discharge burnup. This use of thick fuel rod combined with the P/D (Pitch-to-Diameter) ratio of 1.20 leads to high fuel volume fraction of 61% and slow coolant velocity of 1.28m/sec which is less than the typical limiting value of 2.0m/sec.

Table I. Design specifications

Parameter	Specification
Power (MWe/MWt, BOC/EOC)	37/110
Active core height (cm)	165
Number of rods per FA	169
Smear density of fuel (%)	75
Coolant	Pb
P/D ratio	1.2
Fuel rod diameter (cm)	1.3
Fuel rod pitch (cm)	1.56
Assembly pitch (cm)	20.61
Velocity (m/s)	1.29
Volume fraction_fuel	0.61
Volume fraction_coolant	0.21
Volume fraction_structure	0.18.
Coolant flowing area (cm^2)	5172.8
Inlet temperature (^oC)	320
Outlet temperature (^oC)	425
Mass flow rate (kg/sec)	6980

Fig. 1 shows the radial configuration of the core having no blanket. The fuel assemblies are hexagonal ductless type where 169 fuel rods are arranged in the triangular array. The core consists of 36 fuel driver assemblies. These fuel assemblies are surrounded by the two layers of the lead reflectors that are surrounded by the radial B_4C shields. Also, the core has 10 primary and 3 secondary control rod assemblies for compensating reactivity changes resulted from fuel depletion and temperature changes. At present, the detailed designs of the control assemblies are not available. Fig. 2 shows the radial configuration of the cores having blankets. As shown in Fig. 2, six fuel assemblies having blankets are placed in the second ring of the core.

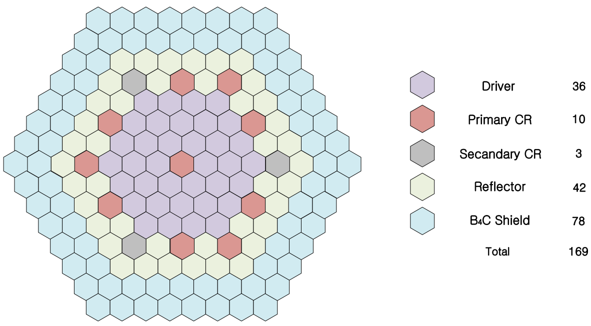

Fig. 1. Radial configuration of the core having no blanket

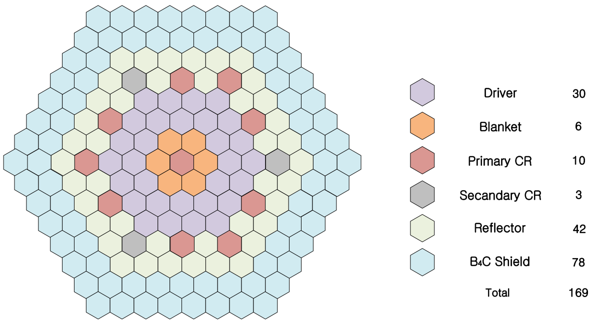

Fig. 2. Radial configuration of the cores having blankets

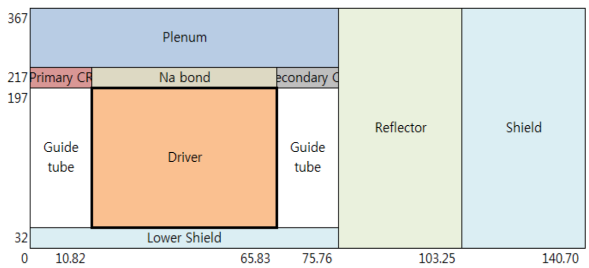

Fig. 3. Axial cut-view of the core having no blanket

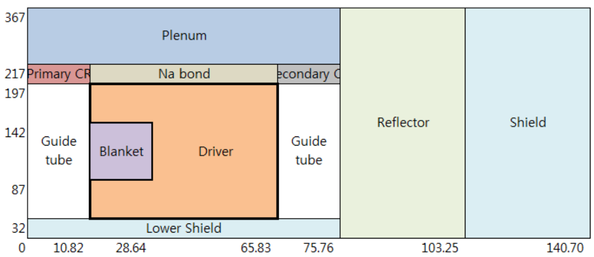

Fig. 4. Axial cut-view of the cores having blankets

Fig. 3 and Fig. 4 show the axial cut-views of the core having no blanket and the cores having blankets, respectively. As shown in Fig. 4, the blankets are placed in the axially central region and the height of blankets is 55cm which was determined to achieve long-life longer than 48 EFPYs.

2.2 Core Performance Analysis and Results

The core depletion calculations are done with the REBUS-3[4] non-equilibrium model for the HEX-Z geometrical models and 25 group cross sections. The starting multi-group cross section library is 150 group MATXS format library which was prepared by KAERI based on ENDF/B-VII.R0. The TRANSX code[5] was used to generate the microscopic cross sections of the ISOTXS foramt by considering the self-shielding effect with Bondarenko method. The core region-wise neutron spectra which were used to collapse the 150 group cross sections into 80 group cross sections were calculated by using the DIF3D code[6] for R-Z geometrical model. Fig. 5 compares the evolutions of the effective multiplication factors for three cores. The reference core is the core having no blanket. The cores having thorium blanket and depleted uranium blanket are denoted by D-Th and D-DU, respectively in Fig. 5. From Fig. 5, it is shown that all of the cores have their life longer than 48 EFPYs. In particular, the core having depleted uranium blanket (denoted by All D in Fig. 5) has the longest life of 58 EFPYs.

Table II compares the core performance parameters for three cores described above. As expected, the core having no blanket has the lowest initial TRU content of 10.6wt% in HM (Heavy Metal). On the other hand, two cores having thorium and depleted uranium blankets have near the same initial TRU contents in HM (for driver fuel) of 11.9wt%. Actually, it was expected that the core having thorium blankets has higher initial TRU content than the one having depleted uranium blanket. We think that the reason why these two cores have almost the same initial TRU content is because the amount of used blanket is relatively small to the amount of driver fuel. The core having thorium blanket has the shortest life of 48 EFPYs while the core having no blanket has its life of 52 EFPYs. On the other hand, the core having thorium blanket has the smallest burnup reactivity of 2020pcm while the core having depleted uranium blanket shows the largest increase of effective multiplication factor due to high breeding capability of the depleted uranium, which leads to the largest burnup reactivity swing. In Table II, it should be noted that all the cores considered have very high fast neutron fluence exceeding the typical limit of 4.0×10^{23} n/cm^2 for cladding integrity. However, we did not consider this factor to determine the core life because it is material aspect and a recladding concept could be applied at the time when the fast fluence limit is reached. In the future, we are planning to consider a study to reduce the fast neutron fluence by using some moderating materials.

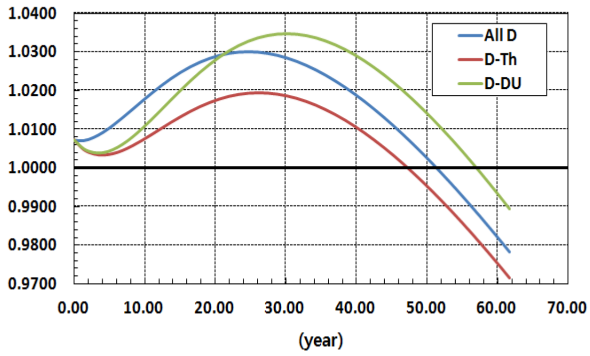

Fig. 5. Comparison of the evolution of the multiplication factors over time

The reactivity coefficients including the control rod worth are summarized and inter-compared in Table III. As shown in Table III, all the cores have small coolant void worth less than 740pcm for the consideration of voiding both in the active core and upper gas plenum. Also, all the cores have all the negative reactivity temperature coefficients except for the one related to the coolant expansion. The coolant expansion reactivity coefficients are very small and our cores have very good inherent safety features from the view points of reactivity temperature coefficients. With the present design of control rod assemblies, the primary and secondary control assemblies give relatively small reactivity worth because the present design of control asssemblies uses natural boron and their locations were not optimized.

Next, we analyzed the axial power distributions. As shown in Fig. 6, only a slight change of axial power distributions from BOL to EOL are observed for the core having no blankets while Fig. 7 and Fig. 8 show that the axial power distributions significantly change from BOL to EOL in the blanket regions for the cores having blankets. Specifically, it is noted that the depleted uranium blanket generates much higher power than the thorium blanket both at BOL and EOL. For the core having depleted uranium blanket, the blankets show higher power density than the driver fuel at EOL.

Fig. 9 compares the changes of the ^{233}U and ^{234}U weight fracation in total uranium for the thorium blanket region over time. As shown in Fig. 9, the thorium blanket region has very high ^{233}U content (weight fraction of ^{233}U in total U) at the initial stage of depletion and ^{233}U content linearly decreases as time. Fig. 10 compares the changes of ^{232}Th and ^{233}U masses in thorium blanket. This figure shows ^{232}Th mass linearly decreases as time while ^{233}U mass initially increases as a result of breeding over time but it shows very small change after the initial stage. Fig. 11 shows the changes of the content of the fissile plutonium isotopes (i.e., ^{239}Pu and ^{241}Pu) in depleted uranium blanket over time. This changing trend of fissile plutonium content is very similar to that of ^{233}U in thorium blanket.

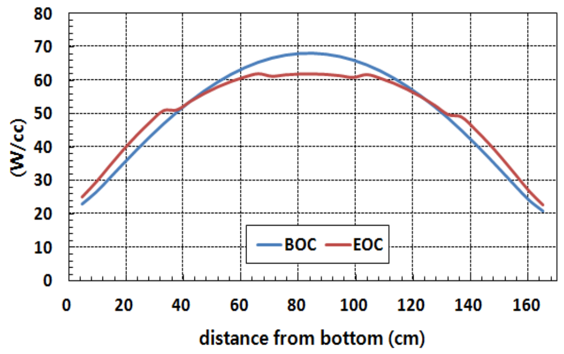

Fig. 6. Axial power distributions of the core having no blanket

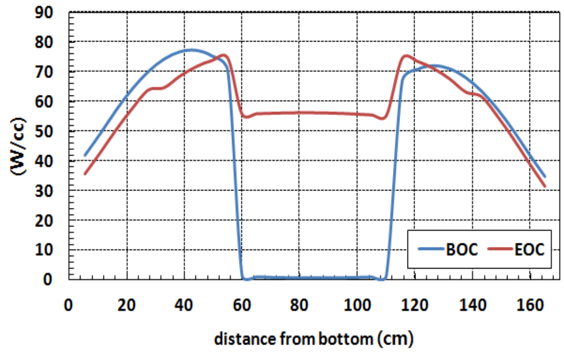

Fig. 7. Axial power distributions of the core having thorium blanket (only for blanket assemblies)

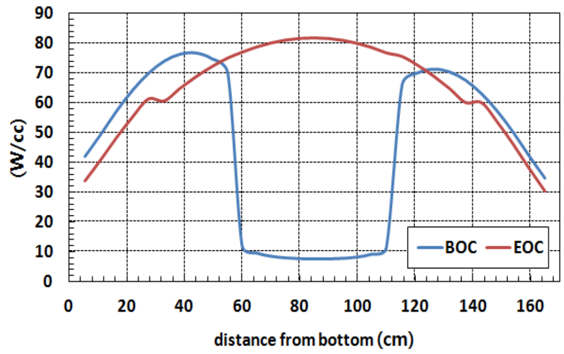

Fig. 8. Axial power distributions of the core having depleted uranium blanket (only for blanket assemblies)

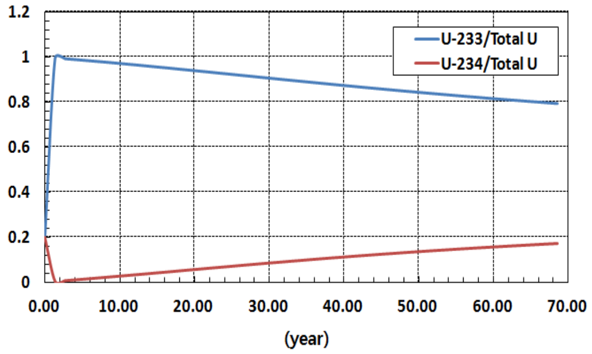

Fig. 9. Comparison of the changes of ^{233}U and ^{234}U contents in thorium blanket

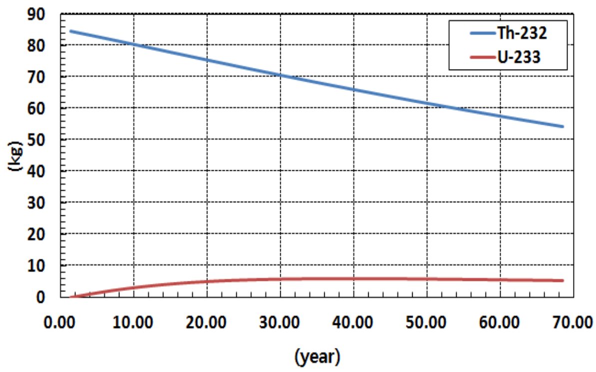

Fig. 10. Comparison of the changes of ^{232}Th and ^{233}U mass in thorium blanket

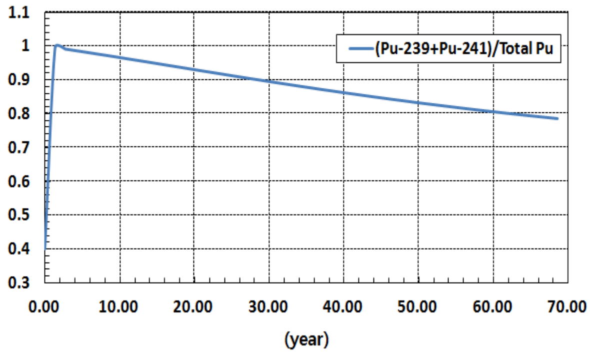

Fig. 11. Comparison of the changes of fissile Pu contents in depleted uranium blanket

Table II. Comparison of the core performances

Parameter	All D	D-B(Th)	D-B(DU)
Driver fuel type	TRU-U-10Zr	TRU-U-10Zr	TRU-U-10Zr
Blanket fuel type	N/A	Th-10Zr	DU-10Zr
Life (cycle length, EFPY)	52	48	58
Initial TRU contents (wt%) in HM (Heavy Metal)	10.64	11.92	11.94
Burnup reactivity swing (pcm)	3060	2020	3470
Average discharge burnup (MWD/kg)			
Driver	152	180	213
Blanket	N/A	141	165
Total reactor	152	143	168
Heavy metal inventories (kg)	2224/1866	2101/1794	2225/1830
Average linear power (W/cm)	108	108	108
Average volumetric power (W/cm^3)	49.5	49.5	49.5
Peak linear power density (W/cm)	202/233	169/282	169/312
Fast neutron fluence (n/cm^2)	1.32x10^{24}	9.78x10^{23}	1.21 x10^{24}

Table III. Comparison of the reactivity coefficients

Parameter	All D	D-B(Th)	D-B(DU)
Fuel Doppler coefficient (pcm/K, 900K, BOC/EOC)	-0.411/-0.271	-0.407/-0.272	-0.479/-0.369
Radial expansion coefficient (pcm/K, BOC/EOC)	-0.489/-0.489	-0.514/-0.499	-0.510/-0.489
Fuel axial expansion coefficient(pcm/K, BOC/EOC)			
Fuel only	-0.464/-0.480	-0.464/-0.483	-0.461/-0.482
Fuel+clad	-0.376/-383	-0.380/-0.391	-0.376/-0.385
Coolant expansion coefficient (pcm/K, BOC/EOC)	0.060/0.069	0.051/0.058	0.055/0.069
Coolant void worth (pcm, BOC/EOC)	620/731	600/612	643/705
Control rod worth (pcm, BOC/EOC)			
Primary	6941/6426	6023/6472	5767/6461
Secondary	232/198	309/217	306/194

3. Summary and Conclusions

In this work, small long-life lead cooled cores are designed and neutronically analyzed in detail. The new cores adopt the relatively small region of blanket, low power density, and thick fuel rods to achieve long-life without refueling. Two different blankets (i.e, thorium and depleted uranium) are considered and they are placed in the axially central region. Additionally, we design a reference core that has the same number of fuel assemblies and the same core height but has no blankets. The core design and performance analyses show that the new cores designed in this study have long-life longer than 45 EFPYs and they have all the negative temperature reactivity coefficients except for small positive reactivity coefficient by coolant expansion. Also, these cores have small coolant void worth less than 750pcm. Also, it was found that all the cores have small peak linear density densities, which means large safety and thermal margin.

Acknowledgement

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