New Sodium Cooled Long-Life Cores with Axially Multi-Driver Regions

Hae Ri Hyun 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, there have been lots of interests and of related works in the studies on the long-life cores[1,2,3]. The CANDLE reactor concept[1] developed by H. Sekimoto is one of these reactors, which leads to a series of similar concepts[2,3] of long-life core. In this concept of long-life core (they are sometimes called B&B (Breed and Burn)), tall blanket is placed above the relatively short driver fuel. In the initial stage of burning, the power by fission is mostly generated in the driver region and it moves into the blanket region. The power and flux distributions that are highly peaked in the axial direction propagates slowly from the driver into the blanket region. This concept of long-life core fully utilizes the breeding of blanket in the fast spectra and it can achieve very high burnup of fuel.

In this work, we introduce new sodium cooled long-life cores rating 600MWe (1800MWt). In these cores, the driver regions are heterogeneously placed into blanket region so as to achieve stabilized and less peaked axial power distribution as depletion proceeds. At present, our study is focused on only two axial driver regions but this concept can be easily extended onto the multi-driver region concept. Also, a sensitivity study on the driver region thickness is performed to show the effect of the amount of driver fuel on the core performances of the new long-life cores. Additionally, we considered one core case having no blanket to show that the long-life having high burnup can be achieved without blanket.

II. Computational Methods and Models

The 150 group cross section library of ISOTXS format is generated using TRANSX code[4] and a MATXS format which was generated with the NJOY code for master nuclides based on ENDF/B-VI.r0. These 150 group cross sections are used in generating core region-wise neutron spectra which are used in collapsing the 150 group cross sections into 80 group and 25 group core region-wise cross sections. The 25 group lumped cross sections for each actinide nuclides are prepared by weighting the microscopic cross sections of the fission products with their fission yields. It is also done with TRANSX. The core depletion analysis is done with the REBUS-3 non-equilibrium cycle model[5] and HEX-Z nodal option. The core physics parameters were evaluated with 80 group cross section and DIF3D HEX-Z nodal option[6]. The decay chain spans the range from ^{232}Th to ^{246}Cm. In this work, the binary metallic fuel of U-10Zr was used. The low enriched uranium is used in the driver region while we considered the depleted uranium as the blanket. The initial multiplication factor was set to 1.007 by adjusting the initial uranium enrichment in the driver fuel.

III. Core Design Study and Performance Analysis

The radial configuration of the cores considered in this work is shown in Fig. 1. The core consists of 372 hexagonal fuel assemblies of a single type. The control system of reactivity consists of 19 primary control assemblies and 6 secondary control assemblies. Table I specifies the main design parameters.

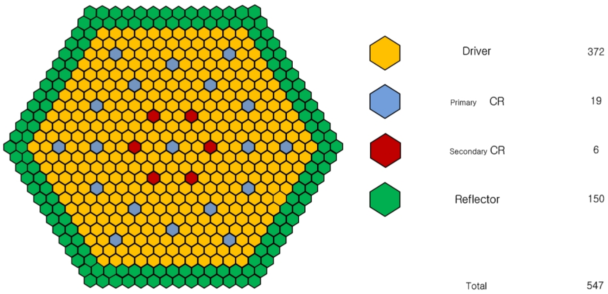

Fig. 1. Reference core configuration

Table I Main design parameters

Design parameter	Specification
Power (MWe/MWt)	600/1800
Number of rods per FA	127
Smear density of fuel (%)	75.0
Duct wall thickness (mm)	3.5
Assembly pitch (cm)	18.92
Rod outer diameter (mm)	14.0
Wire wrap diameter (mm)	1.4
Clad thickness (mm)	0.55
Volume fraction(fuel/coolant/structure)	54.2/28.4/17.4

One fuel assembly having 3.5mm thick duct is comprised of 127 fuel rods. The outer diameter of fuel rods is 1.4cm which is thicker than the conventional SFR (Sodium Cooled Fast Reactor) because high fuel volume fraction is required to achieve long-life of high burnup. It reads to the fuel volume fraction of 54.2%. The cores rate 1800MWt and the average linear heat rate is 180W/cm which is lower than the typical SFR cores.

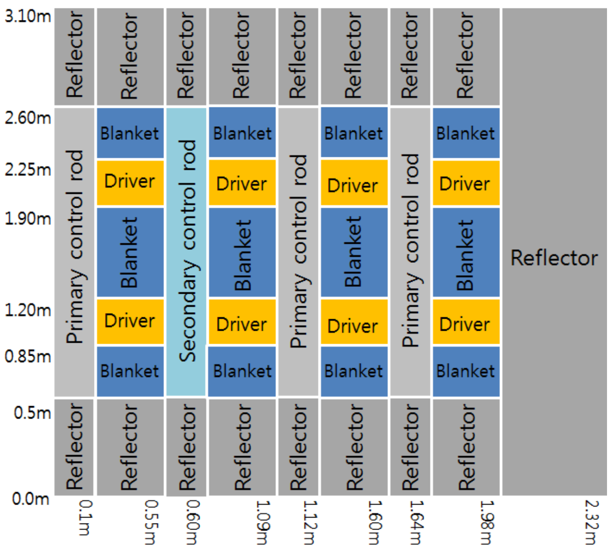

Fig. 2. Axial configuration of Case A core.

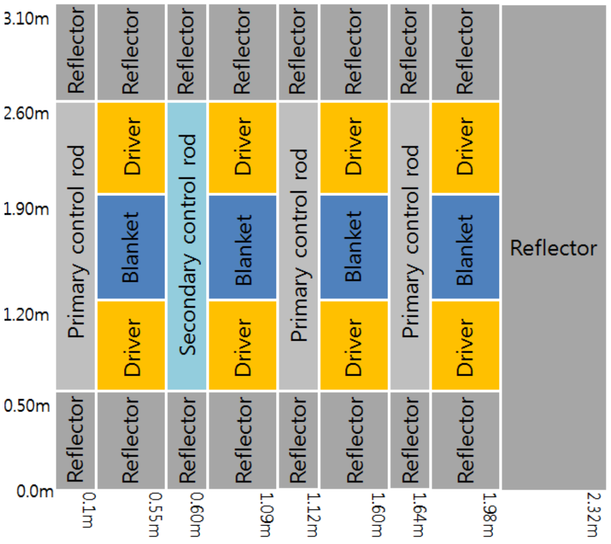

Fig. 3. Axial configuration of Case B core.

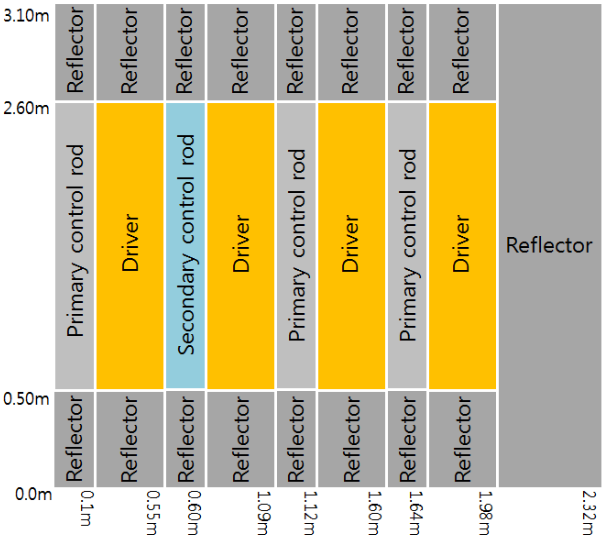

Fig. 4. Axial configuration of Case C core.

On the other hand, the Case C core has no blanket at all. This core is considered to show it is possible or impossible to design long-life core without use of any blanket. Their axial cut-views are shown in Fig. 2, 3, and 4, respectively. Table II summarizes the performances of the long-life cores. The Case A, B, and C cores have 49 EFPYs, 56 EFPYs, and 53 EFPYs, respectively. These cores have 18.93wt%, 12.23wt%, and 9.28wt% initial uranium enrichments of driver fuel, respectively. Also, this table shows that these cores have high discharge burnup of 226GWd/kg, 258GWd/kg, and 245GWd/kg, respectively. In this table, it should be noted that the Case A and B cores have very high linear power densities at BOC and specifically the Case A core has very high linear power density of 935W/cm. So, in the future, we have to further optimize the core layout so as to reduce peak linear power density. But it should be noted that our cores have stabilized axial power distribution of less peaked as the depletion proceeds, which is different from the CANDLE type long-life cores where the peaked axial power distribution propagates without stabilization toward less peaked distribution.

Table II Comparison of performances of long-life cores

Parameter	Case A	Case B	Case C
Fuel type	U-10Zr	U-10Zr	U-10Zr
Initial uranium enrichment (wt%) in driver	18.93	12.23	9.28
Cycle Length, effective full power (EFPY)	49	56	53
Active core height (cm)	210	210	210
Each driver region height (cm)	35	70	210
Average discharge burnup (GWD/t)	225.8	257.5	245.1
Specific power density (MW/t)	12.8	12.7	12.8
Volumetric power density (W/cc)	70.1	69.8	70.0
Cycle average conversion ratio	1.07	0.91	1.00
Heavy metal inventories (kg)	140124	140123	140124
Maximum Neutron Flux ($\#/cm^2 sec$)	1.65×10^{15}	1.73×10^{15}	2.24×10^{15}
Average linear power (W/cm)	180	180	180
Peak linear power density (W/cm, BOC/EOC)	935.4/310.0	570.7 /326.5	449.9 /252.7

Peak fast neutron fluence (n/cm^2)	1.90x10^{24}	1.87x10^{24}	1.87x10^{24}

Table III Comparison of the reactivity coefficients of the long-life cores (BOC/EOC)

Parameter	Case A	Case B	Case C
Fuel Doppler coefficient (pcm/K, 890K)	-0.600/-0.420	-0.465 /-0.443	-0.734/-0.395
Radial expansion coefficient (pcm/K)	-0.795/-0.730	-1.052 /-0.357	-0.524/-0.714
Fuel axial expansion coefficient (pcm/K)			
Fuel only	-0.524 /-0.474	-0.683/-0.604	-0.340/-0.463
Fuel+clad	-0.477/-0.347	-0.672/-0.201	-0.252/-0.333
Coolant expansion coefficient (pcm/K)	0.172/1.129	-0.048/1.137	0.522/1.153
Sodium void worth (pcm, BOC/EOC)	600/3774	-76/3801	1767/3851
Control rod worth (pcm, BOC/EOC)			
Primary	4935/6980	4217/6807	6002/6693
Secondary	2729/691	2325/871	3286/980

In Table III, the reactivity coefficients including sodium void worth and control rod worth are summarized and inter-compared. These values are evaluated at 0 and 49 EFPYs, 56 EFPYs, 53 EFPYs, respectively. The temperature reactivity coefficients are all negative except for the one by coolant expansion. At 0 EFPY, the coolant expansion reactivity coefficients are all small while they are very large at EOC and it seems that they can be problematic. These large coolant reactivity coefficients and sodium void worth at EOC are because the high burnup of the fuels due to long-life irradiations generates lots of TRU actinides and also probably high minor actinide contents. Also, it is noted in Table III that the Case B core has negative sodium void worth at 0 EFPY. This negative sodium void worth is due to the large axial leakage of neutrons resulted from the high initial power generation by the driver region that are located in the end regions of fuel.

Next, we analyzed the evolutions of the multiplication factors over time for the new long-life core. Their lives (or cycle length) are determined by choosing the time interval from BOL when the multiplication factor is larger than unity. For the Case C core having no blanket, the multiplication factor initially increases most rapidly as depletion proceeds while the multiplication factor initially decreases up to ~3 EFPYs and after it the multiplication factor increases up to its maximum value and then linearly decreases in the Case A core.

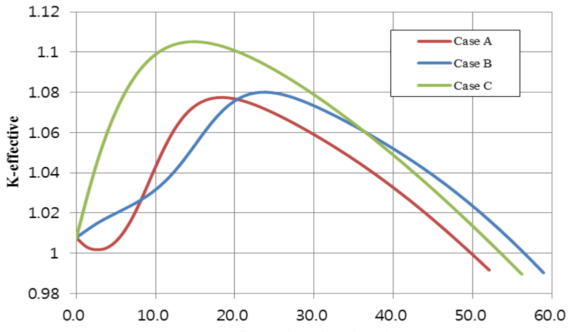

Fig. 5. Comparison of the evolutions of multiplication factors

Next, the evolutions of the axial power distributions over time are analyzed. Figs. 6, 7, and 8 shows the axial power distributions at three different time points for the Cases A, B, and C cores, respectively. These figures show that the new long-life cores have stablized and less peaked axial power distributions as depletion proceeds. For the Case A core, the initial power peaking is very high due to the fact that the power generation is initially in two thin driver regions. For the case B core, the initial axial power peaking is less than the Case A core but the initial peak linear density is still high as shown in Table II.

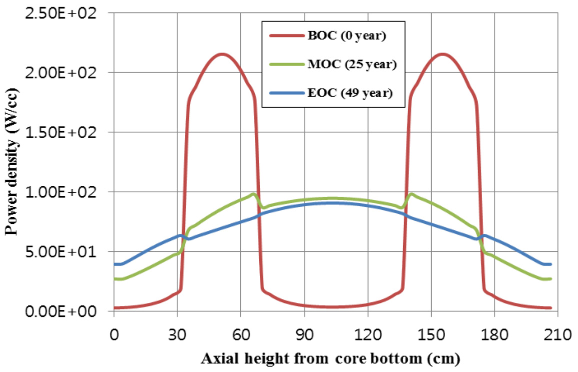

Fig. 6. Comparison of the axial power distribution (Case A core)

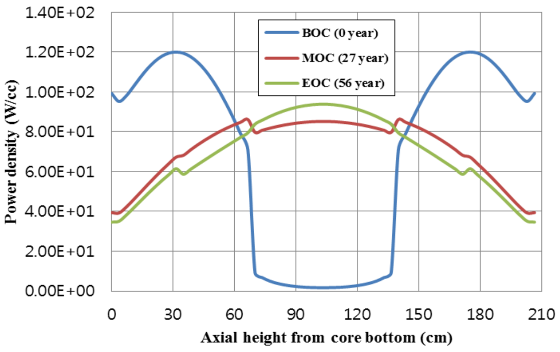

Fig. 7. Comparison of the axial power distribution (Case B core)

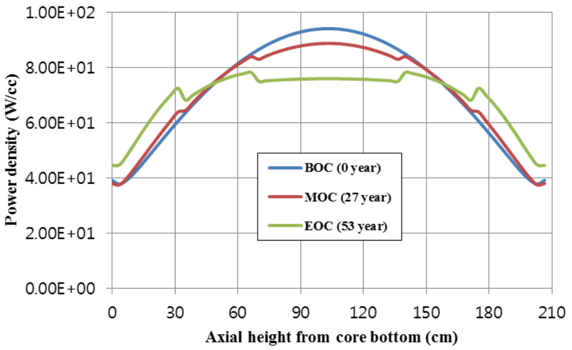

Fig. 8. Comparison of the axial power distribution (Case C core)

For the Case C core having no blanket, the axial power distribution becomes more flat as depletion proceeds because the central fuel depletes more rapidly than the fuels in the outer region.

Finally, we analyzed the effect of the driver region height on the evolution of the multiplication factors for the Case A core configuration. The result is given in Fig. 9. As shown in Fig. 9, the initial increase rate of the multiplication factor becomes higher but the maximum value of multiplication factor does not change so much as the driver height increases.

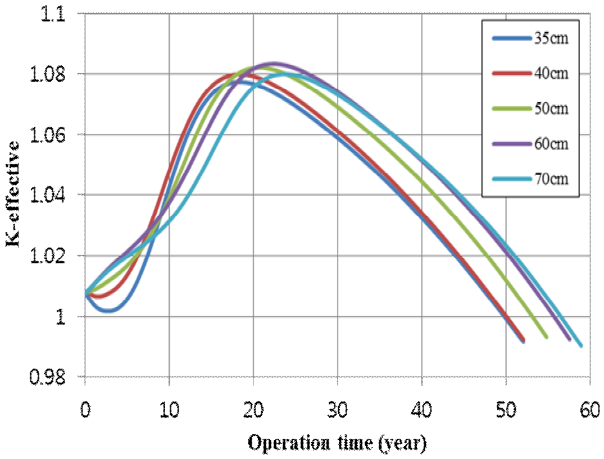

Fig. 9. Evolutions of the multiplication factors for the cores having different driver fuel heights

IV. Summary and Conclusions

In this paper, new sodium cooled long-life fast reactor cores are neutronically designed and analyzed. The cores designed in this paper have two axial driver regions so as to have stabilized and less peaked axial power distributions as depletion proceeds. The results of the core design and analyses show that the cores have very long-lives longer than ~49EFPYs and high discharge burnup higher than 200GWD/kg. Additionally, we considered a long-life core having no blanket. As expected, it was shown that these cores have stabilized and less peaked axial power distribution as the fuel depletes. However, the study shows that the cores having two driver regions still show high initial peaking of the axial power distributions and the core can be optimized by changing the driver fuel height. Also, the cores having two driver regions should be optimized in order to reduce the high sodium void worth at high burnup and it may be achieved by reducing the core height or adding some moderator materials. These topics will be addressed in the future work.

Acknowledgement

This work was supported from National Research Foundation (NRF) of Korea through project No. NRF-2014M2B2A9030201.

REFERENCES

[1] H. Sekimoto, K. Ryu and Y. Yoshimura, “CANDLE: The New Burnup Strategy”, Nucl. Sci. Eng., 139, pp. 306-317 (2001).

[2] Greenspan, E., Heidet, F., “Energy sustainability and economic stability with Breed and Burn reactors”, Prog. in Nucl. Energy 53 (2011) 794-799

[3] T. Tak, D. Lee, T.K. Kim, S. G. Hong, “Optimization study of Ultra-long Cycle Fast Reactor core concept”, Ann. of Nucl. Energy 73 (2014) 145-161

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

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

[6] K. L. Derstine, "DIF3D: A Code to Solve One-, Two-, and Three-Dimensional Finite Difference Diffusion Theory Problems," Argonne-82-64, Argonne National Laboratory, April (1984).