A Study on In-Vessel Shielding Design Concept for the Sodium-cooled Fast Burner Reactor

Sunghwan Yun* and Sang Ji Kim
Korea Atomic Energy Research Institute (KAERI)
989-111 Daedeok-daero, Yuseong-gu, Daejeon, Korea, 305-353
**Corresponding author: syun@kaeri.re.kr*

1. Introduction

In the pool type Sodium-cooled Fast Reactor (SFR), an in-vessel shield is an essential structure to prevent secondary sodium activation (SSA), which passes the intermediate heat exchangers (IHXs), because radioactivated secondary sodium induces a considerable dose in the Steam Generator Building (SGB) [1, 2].

In this paper, two in-vessel shielding design concepts were compared with each other for the Korean Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR), which is similar to a Sodium-cooled Fast Burner Reactor (SFBR). One shielding design concept is using replaceable shield assemblies. This design concept was adopted at the French SUPERPHENIX and Indian PFBR [1,3]. The other design concept is employing a fixed shield. This design concept was adopted at the American S-PRISM and Korean PGSFR [4, 5].

The MCNP6 code [6] with an ENDF/B-VII.0 continuous energy cross-section library was used to prevent problems of multi-group cross-sections and the number of angle quadrature sets reported in reference [7].

2. Calculation Model and Method

A reference calculation model and method for a shielding analysis were the same as those reported in reference [3] except the distance between the IHX and the top of the core. The distance between the IHX and the top of the core in the calculation model is 2 m and the radius of the reactor vessel is 4.3 m as shown in Fig. 1.

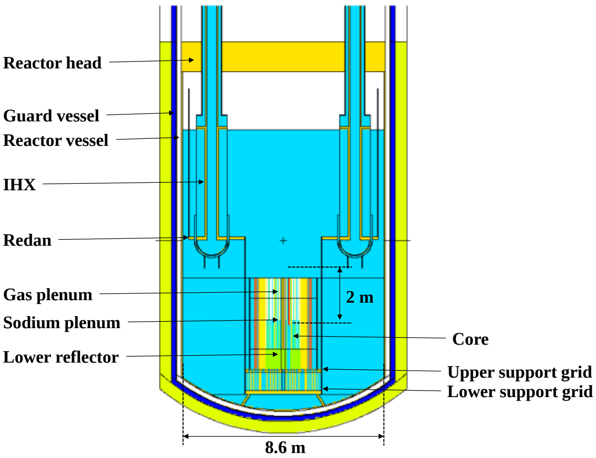


Fig. 1. Axial view of the reference calculation model

The core configuration of the calculation model is shown in Fig. 2. In the reference calculation model, two B_4C shield assembly rings were placed to protect neutron irradiation damage on the core shroud and IVS (In-Vessel-Storage) shroud. Natural boron was adopted in the B_4C shield assembly.

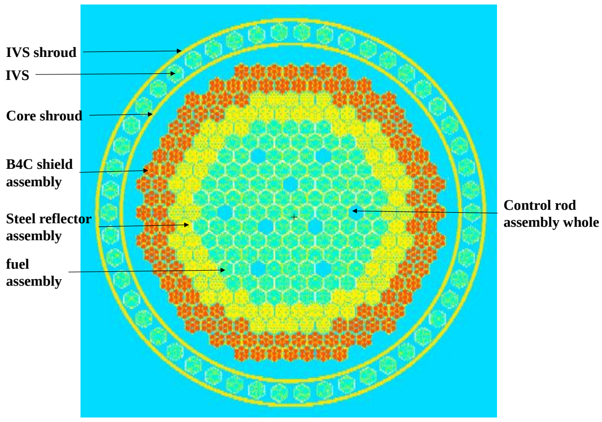


Fig. 2. Core configuration of the reference calculation model

The design limit of the SSA was obtained from reference [1]. In reference [1], 1.6 $\mu Ci/Kg$ was reported for a 19.3 $\mu Sv/h$ worker dose limit in an SGB.

For the calculation of ^{10}B depletion rate at a fixed shield, a 60 year reactor operation time and 0.9 capacity factor were approximated.

3. Analysis Results

3.1 Design Concept Using Replaceable Shield Assemblies

In the design concept using replaceable shield assemblies, the axial shield placed above the core was essential to prevent axial neutron leakage. Hence, the effect of the axial shield was studied first.

The configuration of the considered axial shield is shown in Fig. 3. The axial B_4C shield was placed at the top of the gas plenum and was composed of nineteen B_4C absorber pins. The diameter of the B_4C absorber pin was 1.25 cm.

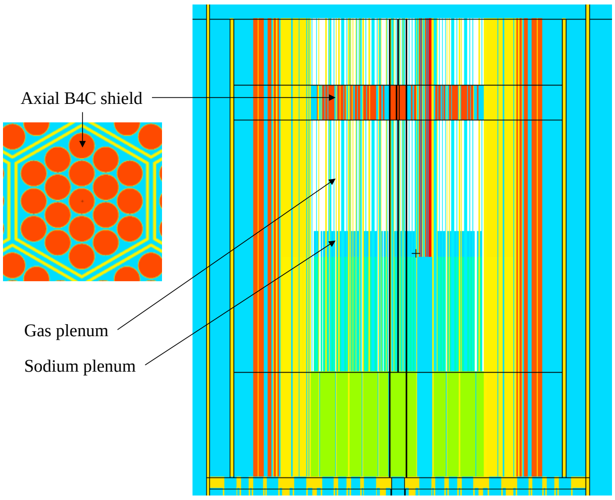


Fig. 3. Configuration of B_4C axial shield

Fig. 4 shows the effect of the axial shield height. A 30 cm height axial shield reduced the SSA in the IHX by a factor of 0.45; however, more than a 30 cm height axial shield did not show a significant improvement in shielding performance.

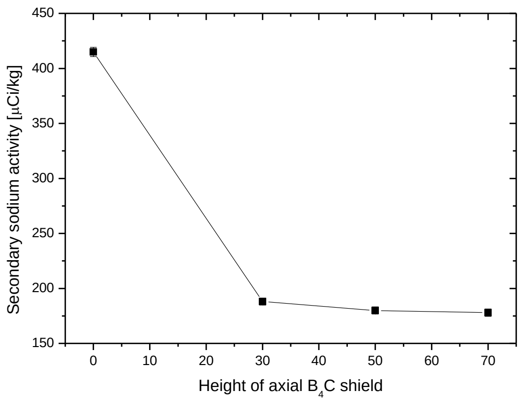
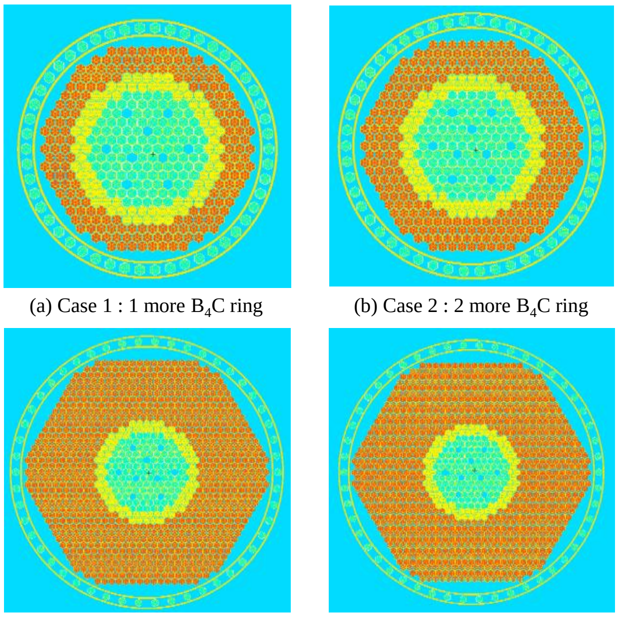


Fig. 4. SSA vs. height of axial shield

Another four cases were considered to investigate the shielding performance according to the number of B_4C shield assemblies. In the first two cases, one and two more B_4C shield assembly rings were added to the reference calculation model, as shown in Fig. 5. The diameters of the IVS shroud, core shroud, and reactor vessel were also increased. In the next two cases, eight and nine more B_4C shield assembly rings were added to the reference calculation model and a 30 cm axial shield was also added.



(a) Case 1 : 1 more B_4C ring

(b) Case 2 : 2 more B_4C ring

(c) Case 3 : 8 more B_4C ring

(d) Case 4 : 9 more B_4C ring

Fig. 5. Core configurations for various number of B_4C shield assemblies

Table I shows SSAs in IHX for the reference calculation model and the four considered cases. For the sodium design of the reference calculation model, eight more B_4C shield assembly rings, i.e., a total of 10 B_4C shield assembly rings- were required with a 30 cm axial shield. Fig. 6 shows the axial configuration and sodium activation distribution for the case 3 model. For the case 3 model, the diameter of the reactor vessel was increased to 10.6 m. In cases of using 90 w/o enriched B_4C shield assembly at both of radial and axial shield are also shown. When using 90 w/o enriched B_4C, the SSA was reduced by 21 % in the reference case. However, adopting 90 w/o enriched B_4C to the case 3 (i.e., the case 5), the SSA was reduced only by 12 %.

Table I. SSAs in IHXs for Various Number of Shield Assemblies

Cases	Activation, *μCi / Kg*
Reference model	414.91±4.21
Reference model with 90 w/o enriched B_4C shield assembly	326.85±3.21
Case 1 : 1 more B_4C ring	259.23±3.35
Case 2 : 2 more B_4C ring	177.59±2.60
Case 3 : 8 more B_4C ring with axial B_4C shield	1.58±0.03
Case 4 : 9 more B_4C ring with axial B_4C shield	1.20±0.02
Case 5 : case 3 with 90 w/o enriched B_4C shield assembly at both of radial and axial shield	1.39±0.02

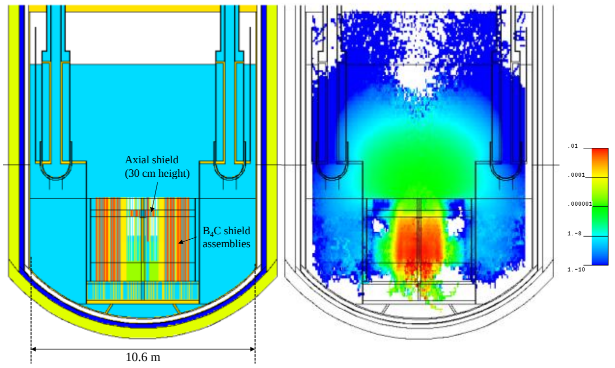


Fig. 6. Axial view of sodium activation distribution for case 3

3.2 Design Using Fixed Shield

To investigate the fixed cylindrical shield design concept, homogenized fixed shield material was considered at the outside of the IVS shroud. The material information of the fixed shield is listed in Table II. Two fixed shields were considered: the first fixed shield (fixed shield 1) located at outside of IVS shroud and the second fixed shield (fixed shield 2) located above the redan plate. The first fixed shield had a 25 cm thickness and 5.5 m height while the second fixed shield had a 4 cm thickness and 3.1 m height.

Table II. Material Data of Fixed Shield

Material	Volume rate, %
B_4C (natural boron)	70
Structure	10
Sodium	5
Vacancy	15
Total	100

Table III and Fig. 7 show the SSA in IHX, the ^{10}B depletion rate, and the sodium activation distributions, respectively. Owing to the relatively lower neutron flux level in the fixed shields compared to that in the core, the ^{10}B depletion rate during a 60 year operation was a negligible amount.

Table III. SSAs in IHXs and ^{10}B Depletion Rate for Fixed Shield Design

SSA, μCi / Kg	1.50 ±0.03
^{10}B depletion rate of fixed shield 1, %	8.69×10^{-6} $\pm2.65\times10^{-7}$
^{10}B depletion rate of fixed shield 2, %	1.62×10^{-10} $\pm9.60\times10^{-12}$

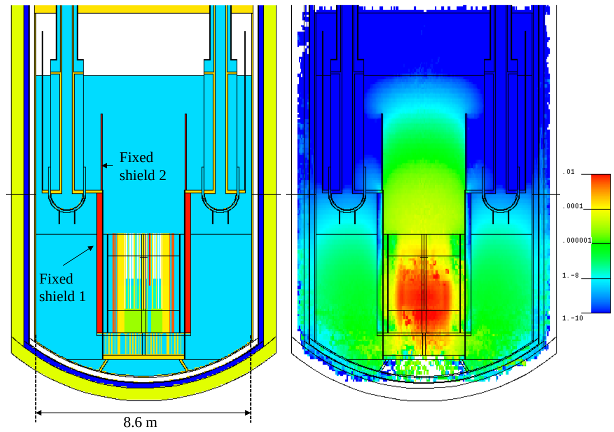


Fig. 7. Axial view of sodium activation distribution for the fixed shield design

4. Conclusions and Discussions

In this paper, two in-vessel shielding design concepts were compared with each other. The diameter of the reactor vessel was increased by 20 % to contain additional B_4C assembly rings in the design concept using replaceable shield assemblies. On the other hand, the diameter of the reactor vessel was not changed in the design concept using a fixed cylindrical shield. Moreover, a negligible ^{10}B depletion rate was also resulted.

Although there are many other parameters that influence the size of the reactor vessel, the configuration of the in-vessel shielding structure is also one of the most important parameters to determine the final size of the reactor vessel for a pool-type SFBR. Therefore, it can be concluded that the cylindrical fixed shield design concept is more efficient than the design concept using replaceable shield assemblies to prevent SSA in the IHX for the SFBR such as the reference calculation model.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP). (No. NRF-2012M2A8A2025622)

References

1. Sunil Kumar D, Keshavamurthy RS, Mohanakrishnan P, Chetal SC, "A feasibility study of ferro-boron as in-core shield material in fast breeder reactors," *Nuclear Engineering and Design*, **240**, 2972(2010).
2. Yoo JW, Kim YJ, Kim YI, and Kang CM, "A Preliminary Shielding Design of 150 MWe Liquid Metal Reactor," *Journal of Nuclear Science and Engineering*, **Supplement 1**, 130(2000).
3. Waltar AE, Todd DR, and Tsvetkov PV, *Fast Spectrum Reactors*, p. 375, Springer Science & Business Media, New York, NewYork (2012).

4. Boardman CE, Dubberley AE, Carroll DG, Hui M, Fanning AW, and Kwant W, "A Description of the S-PRISM Plant," *Proceedings of ICONE 8 (8th International Conference on Nuclear Engineering),* Baltimore, MD USA , April 2-6 (2000).
5. Yun S and Kim SJ, "A Cylindrical Shielding Design Concept for the Prototype Gen-IV Sodium-cooled Fast Reactor," *Transactions of the Korean Nuclear Society Spring Meeting*, May 29-30, Jeju, Korean Nuclear Society(2014) (CD-ROM).
6. Pelowitz DB, et.al., "MCNP6^{TM} USER'S MANUAL", LA-CP-13-00634, LANL(2013).
7. Devan K, Pandikumar G, Alagan M, Gopalakrishnan V, Mohanakrishnan P, "Effects of cross section sets and quadrature orders on neutron fluxes and on secondary ^{24}Na activation rate of a pool type 500 MWe FBR," *Annals of Nuclear Energy*, **30**, 1181(2003).