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Shielding Analysis for the Lower Reflector Block of a PGSFR Fuel Assembly

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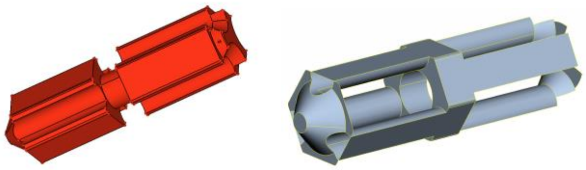
1. Introduction

As a representative of Gen-IV Sodium-cooled Fast Reactor (SFR) concept, a Proto-type Generation-IV Sodium-cooled Fast Reactor (PGSFR) has been developed at the Korea Atomic Energy Research Institute (KAERI). The PGSFR uses single enriched uranium metal-alloy fuel, U-10%Zr, initially and it will be gradually converted into a TRU metal-alloy (U-TRU-10%Zr) fueled core. The fuel assemblies are arranged into a 7-hexagonal-ring configuration, surrounded by stainless steel reflectors and B_4C shields. Each fuel assembly consists of a fuel rod bundle with 217 fuel pins and a lower/upper reflector block. A lower and an upper reflector blocks are installed inside the fuel assembly to reduce the radiation damage on the core support plate and the radioactivity on head access area respectively.



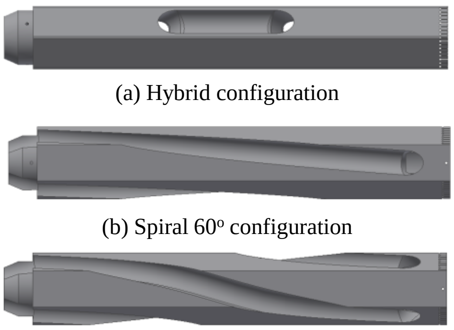
(a) Solid Volume (b) Coolant Volume

Fig. 1. Reflector Block Shape

Figure 1 shows the reflector block design suggested in 2015. It has a 60 degree twist at the lower and upper part in order to maintain the coolant path and simultaneously to diminish the neutron streaming effect. This design can satisfy the radiation damage limit on permanent structure, but it has a high coolant pressure drop caused by the warped coolant path when analyzed using detailed CFD. To address this issue, three reflector block designs which have a lower pressure drop were proposed. In this paper, we analyzed the shielding capability of the three new reflector blocks.

2. New Lower Reflector Block Designs

KAERI's SFR fuel design and nuclear design team suggested three different shapes of reflector block called Hybrid, Spiral 60 and Spiral 120 as shown in Fig. 2. These designs have the same structure and coolant volume fractions as the previous design to keep the shielding capability, but it showed a lower coolant pressure drop due to the elimination of the rapid warped coolant path which was located at the lower and upper part of the previous 2015 design. The 3 reflector block designs have similar pressure drop values and the Hybrid model has the lowest pressure drop.



(a) Hybrid configuration

(b) Spiral 60° configuration

(c) Spiral 120° configuration

Fig. 2. Configuration of New Reflector Block Models

3. Neutron Shielding Evaluations

3.1 Computation Methods

In the previous shielding evaluation, the homogeneous reflector block model was applied to evaluate the DPA on permanent structure by MCNP6 [1] with the continuous-energy ENDF/B-VII.0 library [2]. However, the exact heterogeneous reflector models are required to verify the neutron streaming effect of each new reflector block. Unfortunately, these reflector block models were designed by 3-D CAD program and currently it is not supported to be used in MCNP6. Therefore, Serpent 2 [3] Monte Carlo code was used as an alternative since it can read the 3-D CAD geometry information directly.

To verify Serpent capability against MCNP6 in shielding calculation, a single fuel assembly model with homogeneous axial lower/upper reflector block, shown in Fig. 3, was built with radially periodic boundary condition and axially black boundary condition. The k-effective values between two codes showed good agreement with 67 pcm difference and 10 pcm standard deviation. The flux tally at the bottom of single fuel assembly Monte Carlo model also showed very good agreements as shown in Table I.

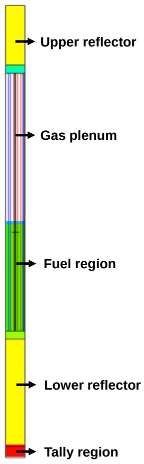


Fig. 3. Single FA Monte Carlo Model

Table I. Flux Tally Result (1σ < 1%)

Upper Energy Boundary	MCNP6	Serpent 2	Rel. Error [%]
0.1 MeV	8.77549E-05	8.73618E-05	0.45%
30 MeV	1.65202E-05	1.64572E-05	0.38%

3.2 3-D Whole Core Simulation

The radial core configuration of PGSFR uranium core is shown in Fig. 4. The core is composed of 112 fuel assemblies, 6 primary control assemblies, 3 secondary control assemblies, 90 reflector assemblies, and 102 B_4C shield assemblies. The fuel assemblies are split into an inner core and an outer core made of 52 and 60 single-enriched fuel assemblies by applying 4/5-batch scheme, respectively. At the cold condition, a fuel assembly consists of 90 cm active fuel region, 125 cm fission gas plenum, and 90/50 cm lower/upper reflector block [4].

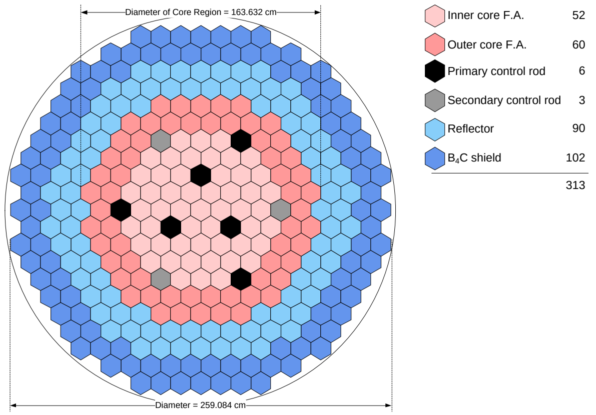


Fig. 4. Radial Core Configuration of PGSFR Uranium Core

Figs. 5 and 6 shows the radial/axial Serpent 2 models. DPA analyses of upper support grid plate were performed only for 5 locations at the bottom of core central region (marked by A to E in Fig. 5). This model described the exact lower reflector block model. It should be noticed that the primary control assemblies were also inserted to consider the downward flux distortion as shown in Fig. 6.

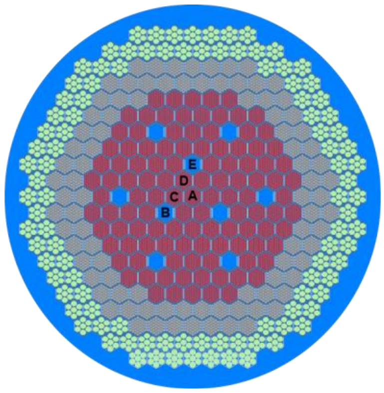


Fig. 5. Radial core model in Serpent 2

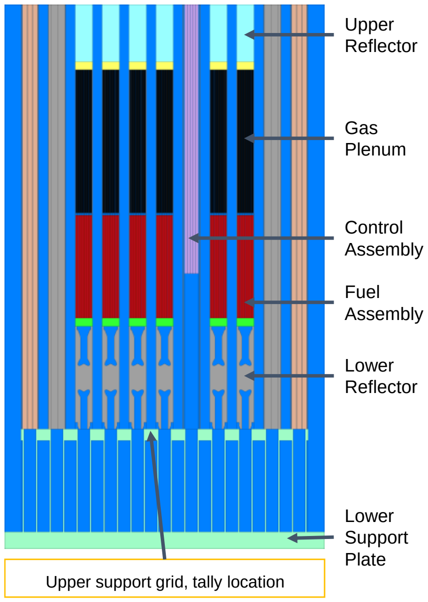


Fig. 6. Axial core model in Serpent 2

The DPA limit for the SS316 support grid is 7.5 which is based on 10% residual uniform elongation [5]. The DPA is defined as Eq. (1) where ***Φ(r,E)*** is neutron flux ($cm^{-2}s^{-1}MeV^{-1}cm^{-3}$), ***N*** is atomic density ($barn^{-1}cm^{-1}$), σ_d is DPA cross sections (barn/atom), E_d is damage energy (eV), and ***C*** is power conversion factor [5].

$$DPA = \frac{\int dV \int \phi(\vec{r},E) dE \sum_{i=1}^{N} N_i \sigma_i^{dpa}(E)}{\sum_{i=1}^{N} 2E_{d,i}} C \qquad (1)$$

Table II. Calculated DPA at Different Locations for lower reflector block models

Code and Models		DPA				
		A	B	C	D	E
MCNP6	2015 Homogeneous	6.03 ± 0.10	6.44 ± 0.10	6.27 ± 0.10	6.31 ± 0.10	6.46 ± 0.10
Serpent 2	2015 Homogeneous	6.14 ± 0.10	6.36 ± 0.10	6.20 ± 0.10	6.12 ± 0.10	6.18 ± 0.10
	2015 Heterogeneous	6.32 ± 0.10	6.35 ± 0.10	6.40 ± 0.10	6.43 ± 0.10	6.69 ± 0.11
	Hybrid	6.68 ± 0.11	6.76 ± 0.11	6.57 ± 0.10	6.51 ± 0.10	6.49 ± 0.10
	Spiral 60	6.58 ± 0.10	6.54 ± 0.10	6.57 ± 0.10	6.71 ± 0.11	6.72 ± 0.11
	Spiral 120	6.78 ± 0.11	6.80 ± 0.11	6.36 ± 0.10	6.41 ± 0.10	6.70 ± 0.11

Table II shows the calculated DPA results at different locations for different lower reflector block models. The result of homogeneous reflector models between two codes indicates that Serpent 2 code underestimates DPA value about 4.3%. The 2015 homogeneous reflector model provides underestimated results compared to the 2015 heterogeneous reflector model by about 8.2%. 3 new reflector block designs have higher DPA value than that of 2015 heterogeneous model and the maximum relative differences model are 6.5%, 4.4% and 7.3% for Hybrid, Spiral 60 and Spiral 120 model, respectively.

4. Summary

The shielding evaluations were performed for the new different reflector block models. In order to describe the complex internal/external structure of the reflector design in detailed, Serpent 2 code was employed instead of MCNP6. The code comparison between MCNP6 and Serpent 2 was examined and confirmed good agreement within a few percent relative error. By the 3-D whole core modeling, the DPA analyses for 3 new reflector block models were conducted and all models satisfied the DPA limit on SS316 support grid plate.

Based on these analysis results and the coolant pressure drop results [6], Hybrid reflector block model was chosen as a candidate reflector block because it showed the lowest coolant pressure drop and similar shielding performance for support grid plate.

ACKNOWLEDGEMENTS

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