Investigation of the homogenization effect in sodium void reactivity in PGSFR

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Abstract. Korea Atomic Energy Research Institute (KAERI) has been developing an SFR to aim at specific design approval of a Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR). In the PGSFR, a metal fueled, blanket-free, pool type SFR concept is adopted to acquire the inherent safety characteristics and high proliferation-resistance. To ensure inherent safety, validation of each reactivity worth that is generated by the core neutronics design code system is an essential work for specific design approval.

In this paper, validation of the modeling error in a SVR (Sodium Void Reactivity) of the PGSFR core was examined by comparing PGSFR core design procedure (multi-group homogeneous MC^2-3/DIF3D-VARIANT) and explicit Monte Carlo modeling (continuous-energy heterogeneous MCNP6) based on the ENDF-B/VII.0 library. SVRs were obtained by direct calculation in both of the MC^2-3/ DIF3D-VARIANT and MCNP6 calculations for core central and peripheral regions.

Key Words: PGSFR, Sodium void reactivity, homogenization effect

1. Introduction

Recently, many researches and developments of sodium-cooled fast reactor (SFR) has been conducted (e.g., PFBR, BN-600, and BN-800, etc.) to maximize uranium utilization and minimize the spent fuel nuclear wastes. Especially for metallic fuelled SFR, it is well known that inherent safety can be achieved even for unprotected events. This inherent safety comes from mainly; i) low operating fuel temperature, and ii) overall negative reactivity feedback. Several important tests of the EBR-II reactor support these inherent safety features based on integral reactivity measurements [1].

Korea Atomic Energy Research Institute (KAERI) has been developing a metallic fuelled SFR to aim at specific design approval of a Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR) [2, 3]. The PGSFR is designed as U-Zr metallic fuelled, blanket-free, and pool type SFR concepts to acquire the inherent safety and high proliferation-resistance. However, to ensure the inherent safety features for PGSFR and to achieve specific design approval, validation of neutronics design code system should be done priory.

Validation of the core neutronics design code system can be divided into two parts: i) validation of the cross-section and ii) verification of a modeling error. Validation of the cross-section for PGSFR core will be finalized at 2017 via the several physics experiments based on the Monte Carlo code system such as the MCNP6 code [4].

For modeling error quantification related with homogenization effect, KAERI has planned to compare results of the current deterministic design code system (multi-group, homogeneous, MC^2-3/DIF3D-VARIANT [5, 6]) and explicit Monte Carlo code (continuous-energy, heterogeneous, MCNP6) based on the ENDF-B/VII.0 library [7]. In this comparison, various

reactivity worth (e.g., doppler, sodium density, control rod worth, etc.) will be analyzed by both codes, and then modeling error for each reactivity worth will be quantified.

In this paper, as a preliminary study, modeling error for sodium void reactivity (SVR) worth is calculated. As well known, the SVR consists of non-leakage component, spectrum hardening, and leakage component that is increased neutron streaming from active core region to non-fuel region [8, 9]. Inner and outer core sodium void situation is analyzed separately, because contribution of each component (spectrum, neutron streaming) is normally different for core central and peripheral regions.

2. Description of the Heterogeneous Monte Carlo PGSFR Model

2.1. Brief description of the PGSFR core design

The PGSFR core utilizes 90-cm-height 19.04 wt.% metal U-10%Zr fuel with 290 cycle length at equilibrium core. The figure 1 shows the radial view of the PGSFR core configuration.

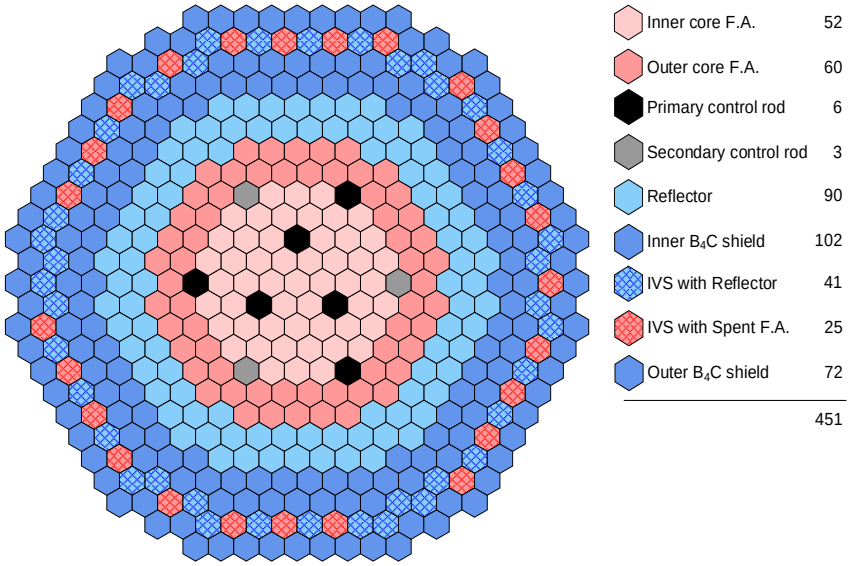

FIG. 1. Radial view of the PGSFR core configuration

As shown in figure 1, the PGSFR core consists of 52 inner fuel assemblies, 60 outer core assemblies, 90 radial reflector assemblies, 174 radial B_4C shield assemblies, and 66 in-vessel storage (IVS) positions. As a control system, six primary control assemblies has 40 wt.% B_4C powder and three secondary control assemblies has 90 wt.% B_4C. More detailed information and characteristics for the PGSFR core design was listed in the Ref. [10]

2.2. MCNP6 Modeling

The radial and axial configurations of the MCNP6 models for the PGSFR at BOEC (Beginning Of Equilibrium Cycle) are shown in Figs. 2 and 3, respectively. Six primary control assemblies are inserted by 26 cm to achieve criticality at BOEC as shown in Fig. 3(a), while all control assemblies are extracted from the active core at EOEC as shown in Fig. 3(b).

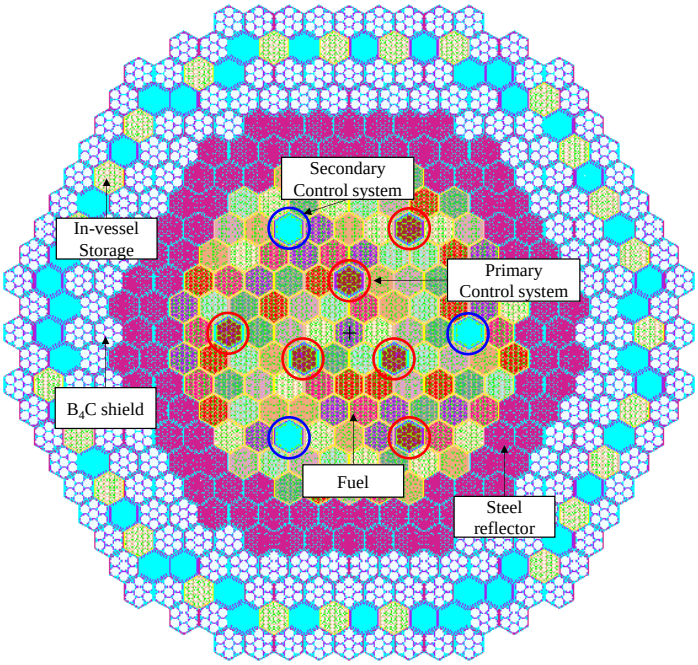

FIG. 2. Radial configuration of the PGSFR MCNP6 model

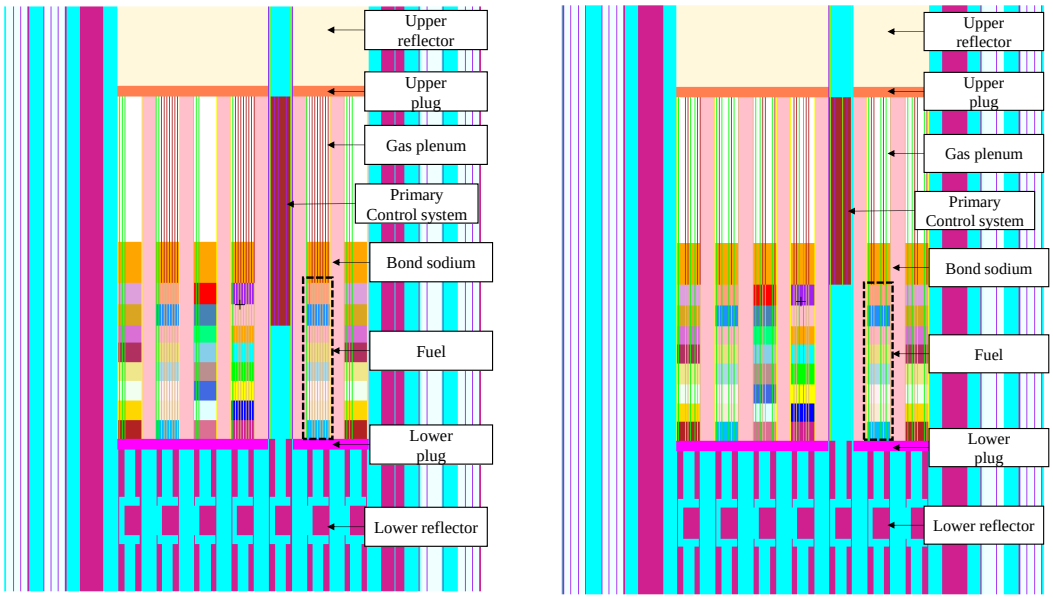

FIG. 3. Axial configuration of the PGSFR MCNP6 model (a: BOEC, b: EOEC)

In heterogeneous MCNP6 model, each fuel pin, cladding, and duct is described explicitly in every fuel, control, steel reflector, B_4C shield assembly. For axial non-fuel regions, explicit gas plenum and bond sodium model is used at above core region, while equivalent lower reflector model is employed at below core region [11]. For lower/upper plug and upper reflector region, homogeneous models are used for sake of simplicity. However, these regions are positioned far from the fuel region or occupying very small portion. Hence, the effect on this homogeneous region on core characteristic is negligible.

3. Description of the Homogeneous Deterministic PGSFR Model

In the PGSFR core design, KAERI has utilized deterministic code system MC^2-3/DIF3D-VARIANT. The steady-state neutron transport analysis code DIF3D-VARIANT solves even-parity based variational nodal transport equation. Therefore, radially, each assembly is treated as one hexagonal node.

In the case of sodium void or density changing situation, only sodium coolant region is perturbed while other structure and fuel component is remained as nominal case. In other words, heterogeneity is increased within assembly when sodium void or density changing is occurred. Unfortunately, PGSFR design code DIF3D-VARIANT is dealing with nodal method so that this kind of heterogeneous changes within assembly may not be considered properly. The numerical results and detail discussion will be shown in Chapter 4.

For DIF3D-VARIANT code, multi-group cross-section for each hexagonal node should be prepared priory. For cross-section generation, MC^2-3 and TWODANT codes are used, and calculation procedure is described in Fig. 4.

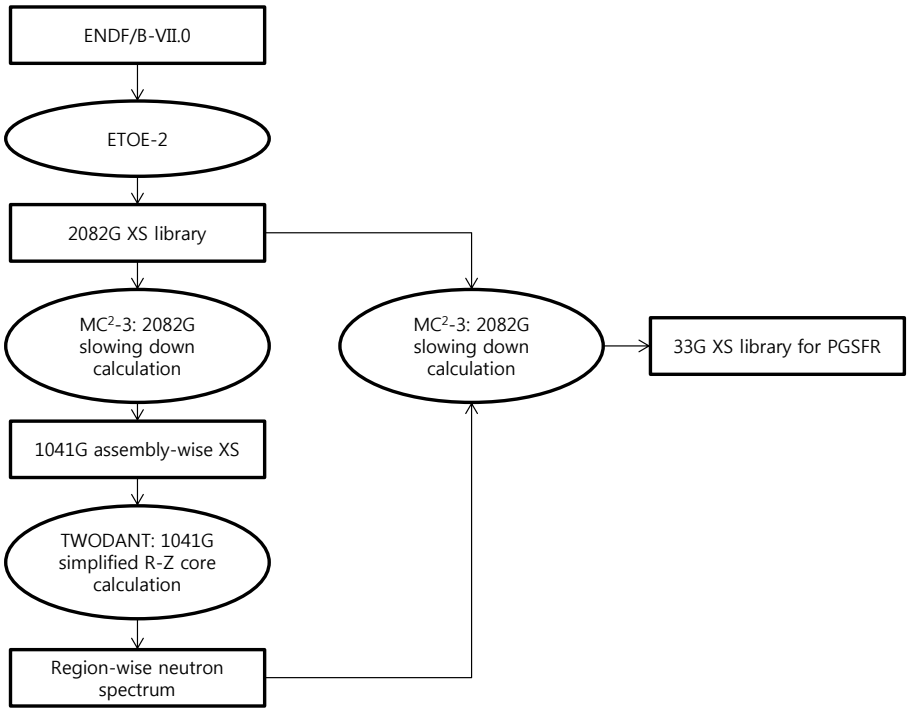

FIG. 4. Nuclear cross-section generation procedure for PGSFR

In MC^2-3 calculation, each types of assembly are treated as 0-D homogeneous mixture. Normally, this is appropriate assumption due to the long mean free path of the fast neutron in SFR. However, in Ref [12], it is reported that heterogeneity effect within control assembly highly affects to the control rod worth and criticality. Therefore, only for control assembly, MC^2-3 calculations are conducted in both ways: i) 0-D homogeneous mixture, and ii) 1-D cylindrical geometry with surrounded by fuels.

4. Numerical Results

4.1.Sodium void reactivity worth

Table 1 and 2 shows the results sodium void reactivity worth by MC^2-3/DIF3D-VARIANT and MCNP6 codes.

For sodium void situation, following three cases are considered:

1. Inner core (IC) void: Active core (fuel) region of inner core fuel assembly + its upper region's sodium coolant are voided
2. Outer core (OC) void: Active core (fuel) region of outer core fuel assembly + its upper region's sodium coolant are voided
3. IC + OC void: Active core (fuel) region of all fuel assembly + its upper region's sodium coolant are voided

Table 1. Sodium void reactivity worth calculation results for PGSFR BOEC core

	MCNP6 (Reference)	MC^2-3/DIF3D-VARIANT (0-D control assembly XS used)		MC^2-3/DIF3D-VARIANT (1-D control assembly XS used)	
	Worth ($)	Worth ($)	Relative error (%)	Worth ($)	Relative error (%)
IC void	-0.599±0.012[a)]	-0.533	-11.0±1.9	-0.539	-9.9±1.9
OC void	-0.896±0.013	-0.865	-3.4±1.3	-0.863	-3.7±1.3
IC+OC void	-1.557±0.013	-1.387	-11.0±0.7	-1.391	-10.7±0.7

[a)] 1 σ uncertainty

Table 2. Sodium void reactivity worth calculation results for PGSFR EOEC core

	MCNP6 (Reference)	MC^2-3/DIF3D-VARIANT (0-D control assembly XS used)		MC^2-3/DIF3D-VARIANT (1-D control assembly XS used)	
	Worth ($)	Worth ($)	Relative error (%)	Worth ($)	Relative error (%)
IC void	-0.527±0.013 [a)]	-0.488	-7.4±2.3	-0.490	-7.1±2.3
OC void	-0.940±0.013	-0.883	-6.1±1.3	-0.882	-6.2±1.3
IC+OC void	-1.572±0.013	-1.402	-10.9±0.7	-1.403	-10.8±0.7

[a)] 1 σ uncertainty

As shown in table 1 and 2, it is shown that modeling error is around -11.0%±0.7 when all fuel assemblies are at the sodium void situation (IC+OC void). And, the effect of considering 1-D heterogeneous control assembly modeling on cross-section generation is almost negligible for sodium void worth.

The SVR can be considered as a combination of i) neutron spectrum hardening effect, ii) radial neutron leakage increasing, and iii) axial neutron leakage increasing. In this paper, sodium is voided at not only fuel part but also its upper axial part. Therefore, in axial direction, there exists large neutron leakage along axial direction in sodium void situation. And this heterogeneity induced strong axial leakage effect is not properly considered and under-estimated in homogeneous MC^2-3/DIF3D-VARIANT calculation. This under-estimated axial leakage will be occurred for both IC and OC in similar ratio, because fuel assembly in IC and OC has same configuration.

For IC void and OC void cases in BOEC core, large discrepancy on IC SVR worth is observed rather than OC void case. Generally, neutron spectrum hardening effect on SVR is dominant component at IC void compared with OC void and it gives positive reactivity for SFRs. Because of this, SVR worth for IC void is closer to 0.0 than OC void case. Hence, when under-estimated axial leakage for MC^2-3/DIF3D-VARIANT is take into account, relative error seems very large for IC void case. In EOEC case, the modeling discrepancy between IC and OC void becomes closer, but the trend is same with BOEC cases.

To confirm the reasons of modeling error difference for IC and OC void cases, various kinds of small local sodium voided cases will be analyzed as a future works.

4.2.Sodium density reactivity worth

In addition to SVR analysis on PGSFR, reactivity worth when sodium coolant density varies is calculated by both MC^2-3/DIF3D-VARIANT and MCNP6 codes.

From normal operation condition, sodium coolant temperature from active core to its upper region is changed to 373.150, 573.150, 773.150, 1173.150K and sodium density is changed according to temperature changes.

Fig. 5 and 6 shows the results of the sodium density reactivity worth for PGSFR at BOEC and EOEC respectively.

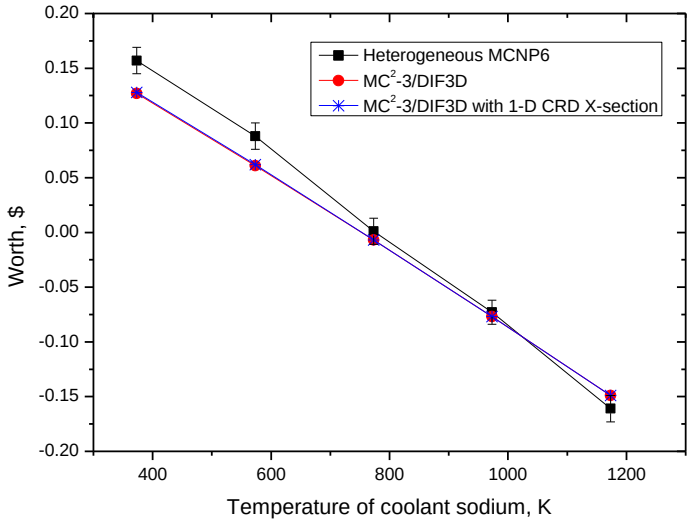

FIG. 5. Sodium density reactivity worth at BOEC

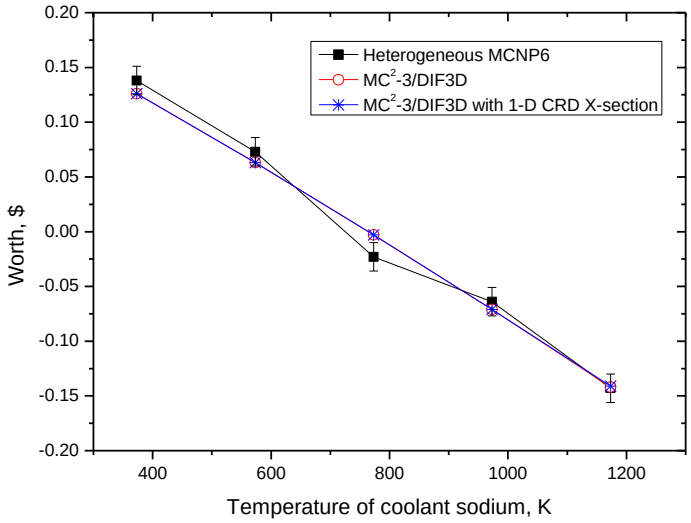

FIG. 6. Sodium density reactivity worth at EOEC

As shown in above figures, two code systems (deterministic and stochastic) agree well except 373.150K and 573.150K at BOEC cases. These two cases are when sodium coolant density is increased compared with normal operation. Up to now, the reason for this larger discrepancy observation is not clear. To resolve this issue, each reactivity component (e.g., spectrum hardening, leakage) comparison will be made as a future work.

5. Summaries

Currently, KAERI utilize the MC^2-3/DIF3D-VARIANT as a PGSFR design code system. Hence, PGSFR core is analyzed based on nodal transport theory. For modeling error quantification related with homogenization effect, in this study, SVR worth and sodium density reactivity worth are calculated by MC^2-3/DIF3D-VARIANT (current PGSFR design code system, homogeneous model) and MCNP6 (heterogeneous model) codes.

From SVR calculation results, it is shown that modeling error for IC and OC sodium void case is estimated about -11.0%±0.7. Quantified modeling error value like this can be used as a bias for each specific reactivity worth. Therefore, modeling error quantification work for PGSFR will be continued to other various kinds of reactivity worth.

It is also observed that IC void and OC void cases show different modeling error values, and large modeling discrepancy is observed for sodium density increasing cases. To figure out these clearly, i) various local sodium voiding analysis, and ii) decomposing SVR worth (spectrum hardening and leakage component) will be conducted as a further study.

6. Acknowledgements

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