Calculation of Excore Detector Responses upon Control Rods Movement in PGSFR

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1. Introduction

The Korea Atomic Energy Research Institute (KAERI) and Argonne National Laboratory are jointly carrying out a broad R&D programme in support of the 150 MWe Prototype Generation-IV Sodium-cooled Fast Reactor (PGSFR) to test and demonstrate the performance of metal fuel containing transuranics (TRU) for commercial SFRs and the TRU transmutation capability of a burner reactor as a part of an advanced fuel cycle system. The PGSFR safety design concept, which aims at achieving IAEA's safety objectives and GIF's safety goals for Generation-IV reactor systems, is mainly focused on the defense in depth for accident detection, prevention, control, mitigation and termination [1].

In practice, excore neutron detectors are widely used to determine the spatial power distribution and power level in a nuclear reactor core. Based on the excore detector signals, the reactor control and protection systems infer the corresponding core power and then provide appropriate actions for safe and reliable reactor operation. To this end, robust reactor power monitoring, control and core protection systems are indispensable to prevent accidents and reduce its detrimental effect should one occur. To design such power monitoring and control systems, numerical investigation of excore neutron detector responses upon various changes in the core power level/distribution and reactor conditions is required in advance.

In this study, numerical analysis of excore neutron detector responses (DRs) upon control rods (CRs) movement in PGSFR was carried out. The objective is to examine the sensitivity of excore neutron detectors to the core power change induced by moving CRs and thereby recommend appropriate locations to locate excore neutron detectors for the designing process of the PGSFR power monitoring systems.

Section 2 describes the PGSFR core model and calculation method as well as the numerical results for the excore detector spatial weighting functions, core power changes and detector responses upon various scenarios of moving CRs in PGSFR. Finally, recommendations regarding the candidate locations of the PGSFR neutron detectors are drawn in Section 3.

2. Methods and Results

2.1 Calculation Model and Method

It is widely recognized that the fission chamber based flux monitoring systems are relatively more sensitive to neutrons (leading to a stronger signal) and wider-range (covering the startup region as well) compared to the ion chamber based flux monitoring systems. In addition, they are designed to function in high gamma radiation environments and do not need massive lead shielding. For that reason, the excore neutron detectors proposed for PGSFR power monitoring systems are the uranium-235 fission chambers.

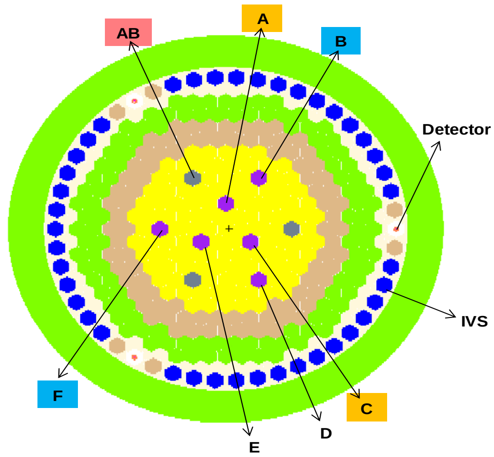

Fig. 1 Radial core layout of PGSFR

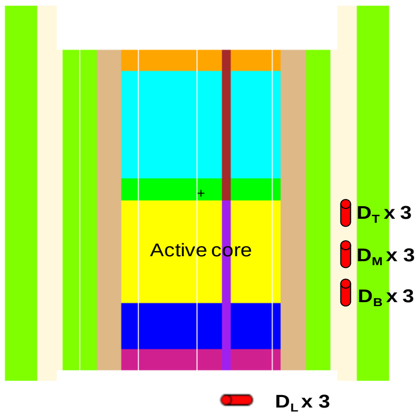

Fig. 2 Axial core layout of PGSFR

Figs. 1-2 show the radial and axial PGSFR core layout, where three detectors were symmetrically located below the core (called the lower detectors- D_L) and nine radial detectors symmetrically located inside the In-Vessel Storage (IVS) and at the bottom, middle, and top of the active core (called the bottom, middle, and top detectors- D_B, D_M, and D_T). Each set of the three symmetric detectors is considered as a candidate for the core power monitoring in this analysis. Also, it should be noted that the possibility of putting neutron detectors above the core is eliminated here because the high temperature in this region can reduce the lifetime of detectors.

The initial core state was assumed to be at RCP (Reactor Critical Point- at which all secondary CRs were fully withdrawn whereas all primary CRs inserted at 39.08 cm- (40% of the core height)). Thereafter, the core was made sub-prompt critical by withdrawing one of the innermost or outermost primary CRs, A (C) or B (F), 9.77 cm (10% of the core height) at 1 mm/sec (total reactivity insertion: $\Delta\rho$ = ~0.3$ or ~0.15$); then the secondary CR AB was fully dropped into the core in 1 sec (called the cases A-AB, C-AB, B-AB, and F-AB).

To predict the response of excore neutron detectors upon changing conditions in a power reactor, the spatial weighting functions which represent individual contributions from specific core locations to the detector response are used. To determine the spatial weighting functions, the point kernel method [2], the discrete ordinate transport method [3] or the Monte Carlo method [4-5] can be adopted. With the Monte Carlo method, one can choose either the forward method or the adjoint method. The Monte Carlo forward method allows the calculation of the value of weighting function of a given point in the reactor. However, it is very time-consuming for calculating the values of weighting functions throughout the whole core since the calculation of the weighting function is a fixed source problem. Therefore, the Monte Carlo adjoint method which is much faster than the forward one was applied in this work to calculate the weighting functions. The well-known MCNP5 code [6] was used for the calculations.

Because of a much longer mean free path of neutrons in fast systems (~10 cm as compared to ~1 cm in PWRs), the neutrons from both the innermost fuel assemblies and the distant ones have higher possibility to leak out of the core and reach the excore detector. Thus, all fuel assemblies of PGSFR were taken into account of calculating their contributions to the detector response.

For the calculation of weighting functions, the fuel assemblies (FAs) were divided into 20 horizontal layers. Then the spatial weighting functions of each FA layer for each detector at two extreme cases, RCP and ARO (All Rods Out), were generated and normalized using the MCNP5 25-group adjoint calculations as illustrated in Eq. (1).

$$\omega_{ijk} = \int \chi(E)\phi^*_{ijk}(E)dE \quad (1)$$

Where $\chi(E)$ is the fission spectrum and $\phi^*_{ijk}(E)$ is the adjoint flux at FA layer (i,j,k). After that, these weighting factors were averaged over each set of the three symmetric detectors to relieve the effect of core radial position on the detector signals.

To make a decision on choosing the appropriate set of spatial weighting functions for the analysis of detector responses upon CRs movement in PGSFR, the Assembly Weighting Functions (AWFs) and Shape Annealing Functions (SAFs) at RCP and ARO were also determined and compared to each other (the reason is explained in the following section). The AWF for the FA (i,j) which represents the excore detector response contributions from individual FAs is calculated by Eq. (2). The SAF for the core layer (k) which represents the relative importance of core axial position to the detector response is calculated by Eq. (3).

$$\omega_{ij} = \sum_k \omega_{ijk} \quad (2)$$

$$\omega_k = \sum_{ij} \omega_{ijk} \quad (3)$$

Meanwhile, the power level at each FA layer was calculated using the FREK (Fast REactor Kinetics code [7]) 25-group diffusion calculations. It is noted that the neutron microscopic cross-sections for 150 neutron energy groups from the KAFAX library (based on the ENDF/B-VII.0 nuclear data and produced at KAERI) were used to generate the 25-group neutron cross-sections for both the MCNP5 and FREK calculations.

Consequently, the detector responses were determined from the excore detector spatial weighting functions and core power distribution as follows.

$$DR(t) = \sum_{ijk} \omega_{ijk} P_{ijk}(t) \quad (4)$$

Where $DR(t)$ is the detector response at time t, $P_{ijk}(t)$ is the power level at the FA layer (i,j,k) at time t, and ω_{ijk} is the excore detector spatial weighting factor of the FA layer (i,j,k).

Three quantities that can characterize the sensitivity of excore neutron detectors to core power changes were examined herein. The first two ones, the relative change in the core power ($\Delta P_r(t)$) and the relative change in DR ($\Delta DR_r(t)$) as defined in Eqs. (5) and (6), reflect the sensitivity of the core power level and of the excore detector upon CRs movement, respectively. The last one, the ratio of the relative change in DR to that in the core power ($\Delta DR_r(t)/\Delta P_r(t)$), reflects the rate of change of the detector response in relation to the core power level.

$$\Delta P_r(t) = \frac{P(t)-P(0)}{P(0)} \quad (5)$$

$$\Delta DR_r(t) = \frac{DR(t)-DR(0)}{DR(0)} \quad (6)$$

Where $X(t)$ and $X(0)$ are the core power (or detector response) at time t and 0.0 sec, respectively (X denotes P or DR).

2.2 Numerical Results

In this part, excore detector spatial weighting functions at ARO and RCP are first generated and compared to consider their application in the calculation of DRs upon CRs movement. Subsequently, the core power changes and DRs are calculated and analyzed to clearly identify how the proposed candidates of excore detectors respond to the core power change induced by CRs movement in PGSFR.

2.2.1 Excore detector spatial weighting functions

As the three dimensional excore detector weighting functions were calculated using MCNP5, it is not intuitive and very time-consuming to compare these weighting functions at different CRs positions, such as at ARO and RCP. Instead, the Assembly Weighting Functions (AWFs) and Shape Annealing Functions (SAFs) at two extreme cases, ARO and RCP, were determined and compared so as to make a decision in choosing appropriate set of spatial weighting functions for this analysis. It is found that there was minor difference between AWFs at ARO and RCP (~4%). Fig. 3 gives an illustration of the AWFs of the bottom detector at ARO and RCP whereas Fig. 4 shows the SAFs for each set of three symmetric detectors at ARO and RCP and their corresponding absolute difference. From Fig. 4, it is found that there was slight difference of SAFs at ARO and RCP within ~0.003 and it is therefore considered practically insignificant. Accordingly, it can be seen that the excore detector spatial weighting functions are very insensitive to the CRs position in the core and the spatial weighting functions at RCP was applied in this analysis.

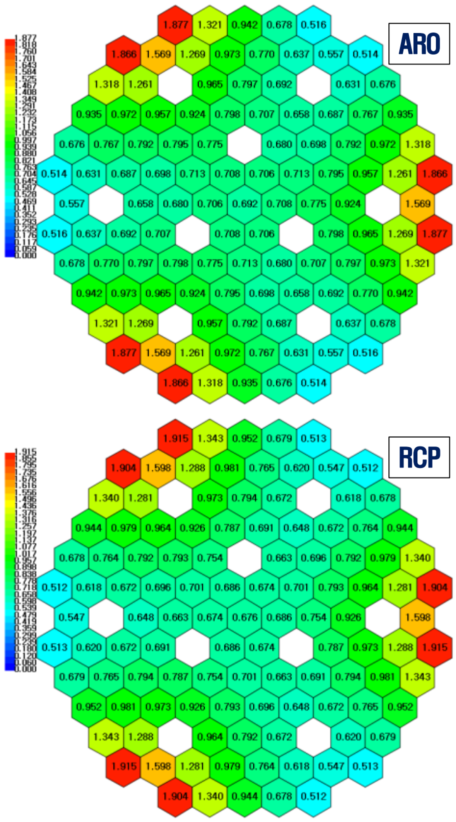

Fig. 3 AWFs of the bottom detector at ARO (up) and RCP (down) x10^2.

2.2.2 Core power changes and detector responses

As the spatial power distribution in the core correlates with the detector response through the spatial weighting functions, it is essential to understand the behaviour of core power with time for the analysis of the detector response. Hence, the axial and radial core distributions in PGSFR were calculated and investigated using the FREK 25-group diffusion calculations to elucidate the transient core power versus time.

The axial and radial core power profiles for the case A-AB (as the primary CR A was withdrawn 9.77 cm at 1mm/sec and then the secondary CR AB dropped in to the core in 1 sec) were illustrated in Figs. 5-10.

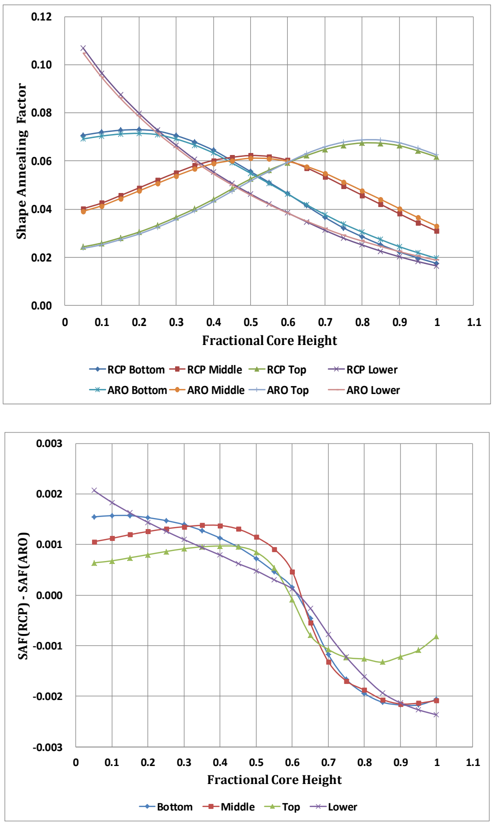

Fig. 4 SAFs (up) and their difference (down) at ARO and RCP.

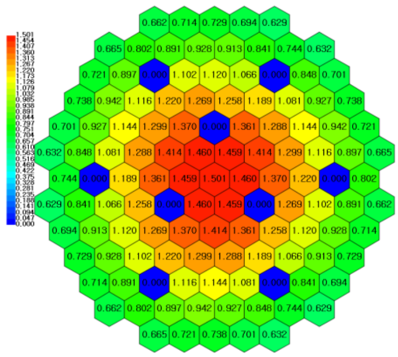

Fig. 5 Normalized radial power distribution at 0.0 sec for case A-AB

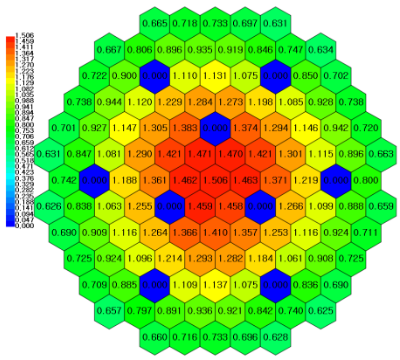

Fig. 6 Normalized radial power distribution after withdrawing A 50.0 sec for case A-AB

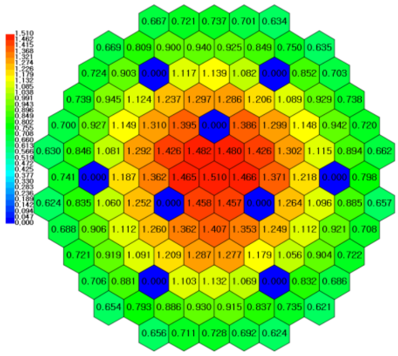

Fig. 7 Normalized radial power distribution at 97.7 sec (start dropping AB) for case A-AB

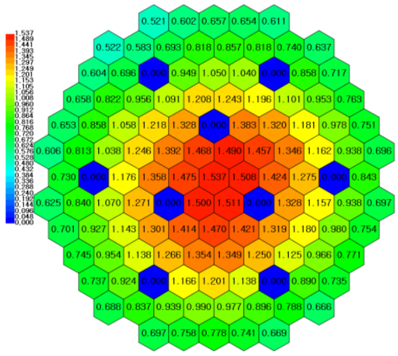

Fig. 8 Normalized radial power distribution at 98.7 sec (AB was fully dropped) for case A-AB

From Figs. 5-7, it can be seen that the normalized radial power distribution increased within ~1.5% around the moved primary CR A and decreased ~0.8% far away from the primary CR A. Comparing Figs. 7-8 shows that the normalized radial power distribution decreased within ~30% around the dropped secondary CR AB and increased within ~8% far away from the secondary CR AB. Nonetheless, it is found that the normalized axial power shape slowly varied with time within ~0.8% as the primary CR A was withdrawn 9.77 cm at 1mm/sec and even when the secondary CR AB was dropped into the core as shown in Figs. 9-10.

The same behaviour of the core radial and axial power distributions was observed for the case C-AB, B-AB or F-AB.

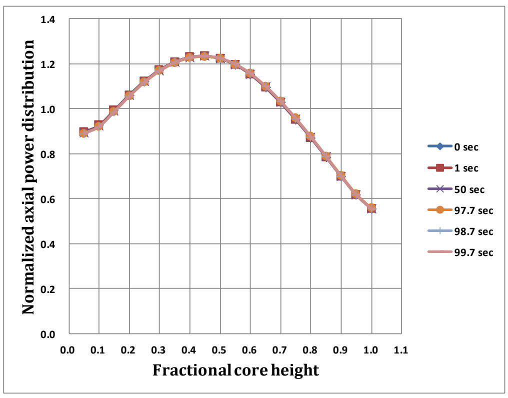

Fig. 9 Normalized axial power distribution for case A-AB

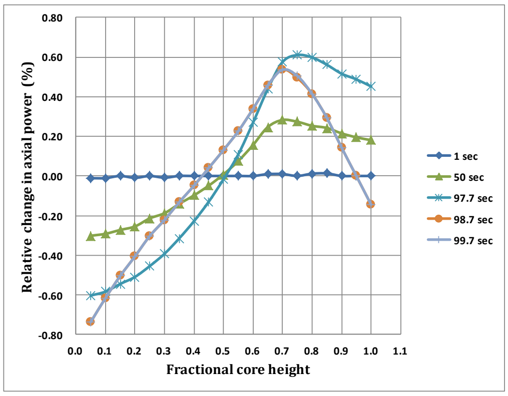

Fig. 10 Relative change in the axial power for case A-AB

After all, the relative changes in the core power and detector response were calculated by using Eqs. (5) and (6). These changes are expected to help clarify how the excore neutron detectors respond to the core power change in PGSFR induced by CRs movement. The results were provided in Fig. 11 for the cases A-AB, C-AB, B-AB, and F-AB. This figure reveals that the primary CRs A and B showed the same behaviour in the relative changes in DR and core power with the primary CRs C and F, respectively. However, the relative changes in DRs and core power levels are well overlapped in all cases and it is thus not possible to distinguish them in this figure.

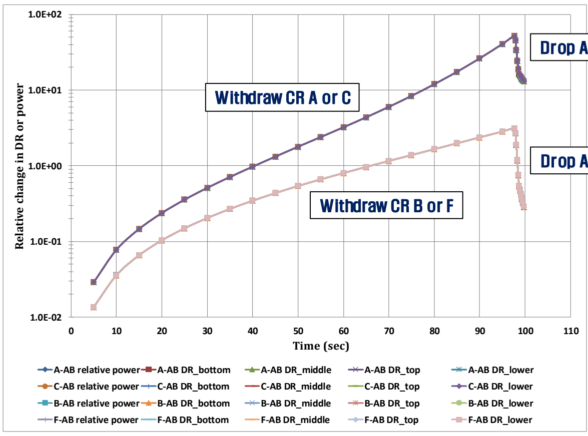

Fig. 11 $\Delta D_r(t)$ or $\Delta P_r(t)$ as A, C, B or F was withdrawn 9.77 cm at 1 mm/sec and then AB dropped into the core in 1 sec

Hence, the ratio of the relative change in DR to that in the core power ($\Delta DR_r(t)/\Delta P_r(t)$) was determined and shown in Figs. 12-15. As a primary CR was withdrawn, Figs. 12-13 indicate that the top and middle detectors followed well the core power increase while the lower and bottom detectors showed a somewhat lower sensitivity. Especially, the top detector overestimated the core power level, it is thus conservatively safe. However, it can be seen that the lower and bottom detectors still functioned well in this case because they exhibited a minor underestimation of core power of less than ~0.5%. As the secondary CR AB was dropped into the core, Figs. 14-15 show that the lower detector followed well the core power decrease whereas the radial detectors showed a decreasing sensitivity. Nevertheless, the radial detectors are considered to be better than the lower detector in terms of inherent safety because they overestimated the core power level.

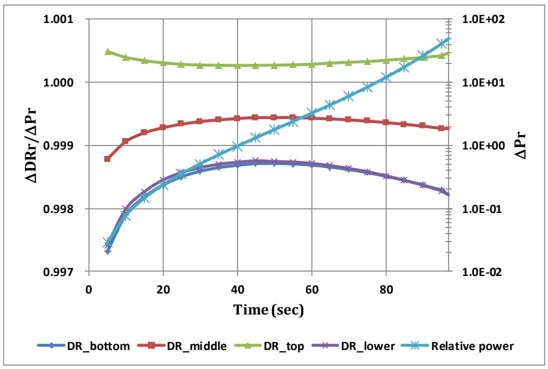

Fig. 12 $\Delta D_r(t)/\Delta P_r(t)$ as the primary CR A or C was withdrawn 9.77 cm at 1 mm/sec

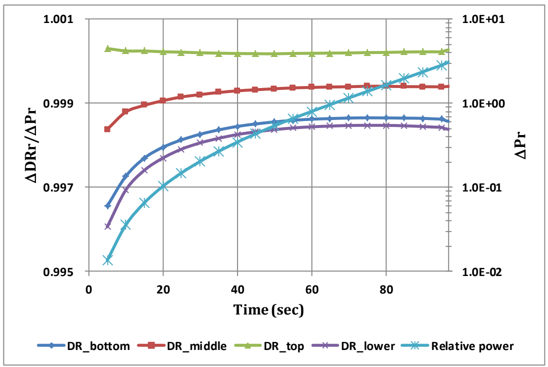

Fig. 13 $\Delta D_r(t)/\Delta P_r(t)$ as the primary CR B or F was withdrawn 9.77 cm at 1 mm/sec

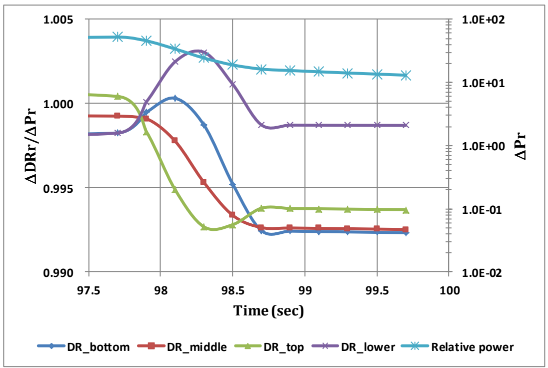

Fig. 14 $\Delta D_r(t)/\Delta P_r(t)$ as the secondary CR AB was dropped in to the core in 1 sec, given the primary CR A or C withdrawn 9.77 cm at 1 mm/sec

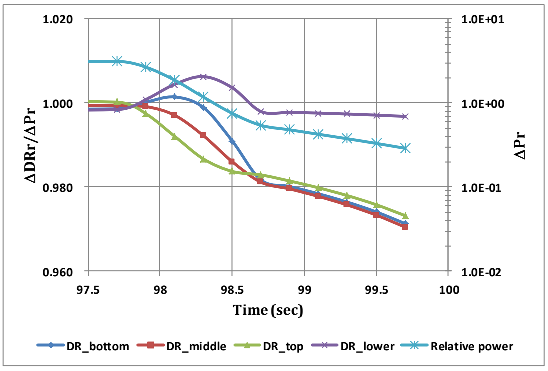

Fig. 15 $\Delta D_r(t)/\Delta P_r(t)$ as the secondary CR AB was dropped in to the core in 1 sec, given the primary CR B or F withdrawn 9.77 cm at 1 mm/sec

3. Conclusions

Numerical analysis of excore neutron detector responses to core power changes induced by CRs movement in PGSFR was performed in this study to figure out the appropriate locations to locate excore detectors for the designing process of the PGSFR power monitoring systems. First, the excore detector spatial weighting functions at ARO and RCP were calculated using the MCNP5 25-group adjoint calculations and compared to each other to choose the appropriate set of spatial weighting functions for this analysis. Second, the spatial power distribution in the core was calculated using the FREK 25-group time-dependent diffusion calculations. Finally, the detector responses were calculated and analyzed through these spatial weighting functions and spatial power distribution.

As a primary CR was withdrawn, the top and middle detectors were found to follow the core power increase better than the bottom and lower detectors. Particularly, the top detector is conservatively safe because it overestimated the core power level. However, the lower and bottom detectors still functioned well in this case because they exhibited a minor underestimation of core power of less than ~0.5%. As a secondary CR was dropped into the core, the lower detector was found to follow the core power better than the radial detectors, which showed a decreasing sensitivity. Nonetheless, the radial detectors are considered to be better than the lower detector in terms of inherent safety because they overestimated the core power level.

In conclusion, the top and middle detectors, which responded well to the core power increase induced by CRs withdrawal, are found to be the best choices for the PGSFR power monitoring systems. In addition, the bottom and lower detectors can be considered as other candidates thanks to their minor underestimation of core power rise of less than ~0.5%.

Acknowledgement

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

REFERENCES

[1] Jeong H.Y., Safety Approach of PGSFR in Korea, The 3rd Joint GIF-IAEA Workshop on Safety Design Criteria for Sodium-cooled Fast Reactors, IAEA, Vienna, Austria, February 26-27, 2013.

[2] Crump M.W., Lee J.C., Calculation of Spatial Weighting Functions for Ex-Core Detectors, Nuclear Technology, 41, pp. 87-96, 1978.

[3] Ahn J.G., Cho N.Z., Generation of Spatial Weighting Functions for Ex-core Detectors by Adjoint Transport Calculation, Nuclear Technology, 103, pp. 114-121, 1993.

[4] Berki T., Calculation of Spatial Weighting Functions for Ex-core Detectors of VVER-440 Reactors by Monte Carlo Method, International Conference: Nuclear Energy for New Europe 2003, Portorož, Slovenia, September 8-11, 2003.

[5] Farkas G. et al, Computation of Ex-core Detector Weighting Functions for VVER-440 Using MCNP5, Nuclear Engineering and Design, 261, pp. 226-231, 2013.

[6] X-5 Monte Carlo Team, MCNP - A General N-Particle Transport Code, Version 5 - Volume I: Overview and Theory, LA-UR-03-1987, Los Alamos National Laboratory, 2003.

[7] Bae M.H., Cho J.H., Joo H.G., MARS/FREK Spatial Kinetics Coupled Fast Reactor System Code: Initial Development and Assessment, Transactions of ANS Annual Meeting, Vol. 101, No. 1, pp. 728-729, 2009.