Nucl. Sci. and Tech, Vol.5, No. 2 (2015), pp. 15-25

Nuclear Science and Technology

Journal homepage: https://jnst.vn/index.php/nst

Calculation of excore detector weighting functions for a sodium-cooled TRU burner mockup using MCNP5

Pham Nhu Viet Ha*, Min Jae Lee, Sunghwan Yun, and Sang Ji Kim

Korea Atomic Energy Research Institute
1045 Daedeok-daero, Yuseong-ku, Daejeon, 305-353, Korea
**Email: phamha@kaeri.re.kr*

Abstract: Power regulation systems of fast reactors are based on the signals of excore detectors. The excore detector weighting functions, which establish correspondence between the core power distribution and detector signal, are very useful for detector response analyses, e.g., in rod drop experiments. This paper presents the calculation of the weighting functions for a TRU burner mockup of the Korean Prototype Generation-IV Sodium-cooled Fast Reactor (named BFS-76-1A) using the MCNP5 multi-group adjoint capability. For generation of the weighting functions, all fuel assemblies were considered and each of them was divided into ten horizontal layers. Then the weighting functions for individual fuel assembly horizontal layers, the assembly weighting functions, and the shape annealing functions at RCP (Reactor Critical Point) and at conditions under which a control rod group was fully inserted into the core while other control rods at RCP were determined and evaluated. The results indicate that the weighting functions can be considered relatively insensitive to the control rods position during the rod drop experiments and therefore those weighting values at RCP can be applied to the dynamic rod worth simulation for the BFS-76-1A.

Keywords: *SFR, TRU burner, BFS-76-1A, excore detector, weighting function, MCNP5*

I. INTRODUCTION

Sodium-cooled Fast Reactor (SFR) has been widely recognized as one of the most promising and attractive energy sources for future generations since it can help efficiently utilize the uranium resources and drastically minimize the burden of nuclear waste from nuclear power plants by closing the fuel cycle. In response to this recognition, the Korea Atomic Energy Research Institute (KAERI) had elaborated an advanced SFR concept for transuranics (TRU) burning in the conceptual design phase (2007-2011) of the long-term advanced SFR R&D plan towards the construction of an advanced SFR demonstration plant by 2028 [1][2]. Recently, KAERI has been collaborating with the US Department of Energy's Argonne National Laboratory to develop the 150 MWe Prototype Generation-IV Sodium-cooled Fast Reactor (PGSFR) for testing and demonstrating the performance of TRU bearing metal fuel for commercial SFRs and the TRU transmutation capability of a burner reactor as a part of an advanced fuel cycle system [3][4].

For the demonstration of the metal fueled TRU burner core concept and securing of the reactor physics database for design code validation, KAERI has been also collaborating with the Institute of Physics and Power Engineering (IPPE) in Russia for conducting reactor physics experiments [3][4]. Correspondingly, four critical assemblies were

https://doi.org/10.53747/jnst.v5i2.189
Received 23 September 2015 , accepted 23 October 2015

constructed in the IPPE BFS-1 or BFS-2 facilities (called BFS-73-1, BFS-75-1, BFS-76-1A, and BFS-109-2A), representing either the metal uranium fuel (U-10Zr) loaded SFR concept developed in Korea in the late 1990's [1] or the current PGSFR design [3][4]. Especially, the BFS-76-1A, which stands for the current PGSFR core, is a mockup of 300 MWe class TRU burner design without a blanket, simultaneously loaded with uranium and U-Pu metal fuels, and characterized by a low conversion ratio, a high burnup reactivity swing, and the consequent deep insertion of the primary control rods at the beginning of the equilibrium cycle. Reactor physics experiments in the BFS-76-1A were aimed to obtain measured data on critical mass, spectral indices, fission rate distribution, sodium void and axial expansion effects, and control rod mockup worth. In particular, the information on control rod mockup worth is very important and requires careful evaluation because of its safety implications.

For that reason, a dynamic rod worth simulation method applicable to SFRs needs to be developed and then applied to the BFS-76-1A for validating the measured control rod mockup worths. To simulate the pseudo excore detector signals needed for inferring the dynamic worth of control rods during the rod drop experiments, the excore detector spatial weighting functions which represent individual contributions from specific core locations, i.e., fuel assemblies, fuel rods or portions of rods, to the detector signal are required in advance [5-8]. It should be noted that the power regulation system of a fast reactor is based on the signals of excore neutron detectors. The detector signal contribution from each fuel assembly depends not only on the power of the fuel assembly but also on its position in the core. The excore detector spatial weighting functions establish correspondence between the spatial core power distribution and the signal of excore detectors.

In this paper, the excore detector spatial weighting functions for the BFS-76-1A were calculated and evaluated for further use in the dynamic rod worth simulation. For generation of the spatial weighting functions, all fuel assemblies were considered and each of them was divided into ten horizontal layers. Then the spatial weighting functions for individual fuel assembly horizontal layers at RCP (Reactor Critical Point) and at the condition under which one control rod group was fully inserted into the core while other control rods at RCP were determined using the MCNP5 150-group adjoint calculations and inter-compared. The results show that the spatial weighting functions were relatively insensitive to the control rods position during the rod drop experiments and therefore those weighting values at RCP can be applied in the dynamic rod worth simulation for the BFS-76-1A.

The calculation methodology is presented in Section II. The results are provided and discussed in Section III. Finally, concluding remarks are drawn in Section IV.

II. CALCULATION METHODOLOGY

The BFS-76-1A mockup consists of 326 LEZ-Pu assemblies, 488 LEZ-U assemblies, 322 HEZ-Pu assemblies, 648 HEZ-U assemblies, and the outer layers of relector, B4C shield, and radial shield assemblies as shown in Fig. 1, where two excore neutron detectors were located outside the radial shield and symmetrically in the radial direction for this study (In Fig. 1: 101= LEZ-Pu; 201= LEZ-U; 301= HEZ-Pu; 401= HEZ-U; 501, 601= primary, secondary control rods; 701= reflector; 801= radial shield; 901= B4C shield; 10= void; LEZ and HEZ= Low and High Enrichment Zones). In the vertical direction, each detector is located ~10 cm above the bottom of the active core. The detectors are the BF_3 proportional counters. They are cylinders of BF_3 with a radius of 2.5 cm and a height of 40 cm. The cylinders are covered by a polyethylene moderator layer with a thickness of 5.0 cm to enhance the detector sensitivity.

The excore detector response at arbitrary time *t* is defined by [6]

$$DR(t) = \int P(r,t)\omega(r)dV \tag{1}$$

where $P(r,t)$ is the core power at position r and time *t*; $\omega(r)$ the spatial weighting function at postion r; V the total core volume; it should be noted that the unit of $DR(t)$ is arbitrary.

In practice, the spatial weighting functions for the excore detectors can be generated using either the point kernel method [5], the discrete ordinate transport method [6], or the Monte Carlo method [7][8]. It is noted that an advantage of the Monte Carlo method is the capability of modeling reactor configurations with arbitrary geometrical complexity. With the Monte Carlo method, one can also choose either the forward method or the adjoint method. The Monte Carlo forward method allows the calculation of the weighting function value of a given point in the reactor and therefore gives more detailed results than the adjoint method. Additionally, the forward method makes it possible to avoid the approximations which stem from the homogenization of the cross sections of the assembly material and from the use of group-wise data. Nevertheless, since the calculation of the weighting function is a fixed-source neutron transport problem, the adjoint method is much faster than the forward method. Especially, it will be very time-consuming to generate the weighting functions using the forward method if a large number of the specific core locations are taken into account.

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 be “seen” by the excore detector. Thus, all fuel assemblies of the BFS-76-1A (1784 assemblies) were taken into account for calculating their contributions to the detector response; whereas only the contributions from the peripheral fuel assemblies located close to the detector are considered significant for PWRs. Therefore, the Monte Carlo adjoint method, which is much faster than the forward method as discussed above, will be applied in the calculation of the weighting functions for the BFS-76-1A using the well known MCNP5 Monte Carlo N-Particle Transport Code [9][10]. Based on the adjoint method, the spatial weighting function is given by [6].

$$\omega(r_i) = \int \chi(E)\phi^*(r_i,E)dE \tag{2}$$

where $\omega(r_i)$ is the spatial weighting factor at position r_i, $\chi(E)$ the fission energy spectrum, and $\phi^*(r_i,E)$ the adjoint flux at position r_i and neutron energy *E*.

For the calculation of the weighting functions, each fuel assembly (FA) of the BFS-76-1A (indexed by (*i*,*j*)) was divided into 10 horizontal layers (each layer was indexed by *k*, *k* = 1, 2, …, 10). Based on Eq. (2), the three-dimensional spatial weighting functions of each FA layer (*i*,*j*,*k*) for each detector at RCP (Reactor Critical Point- at which all secondary control rods were withdrawn out of the core and all primary control rods inserted into the core ~42% of the core height) and at the condition under which one control rod group (Group 1, 2, or

3; see Fig. 1) was fully inserted into the core while other control rods at RCP (hereafter called the case G1IN, G2IN, or G3IN respectively) were generated (using the MCNP5 150-group adjoint calculations) and normalized over the whole core by

$$\omega_{ijk} = \frac{\int \chi(E)\, \Phi^{*}_{ijk}(E)\, dE}{\sum_{ijk} \int \chi(E)\, \Phi^{*}_{ijk}(E)\, dE} \cong \frac{\sum_{g=1}^{150} \chi_g\, \Phi^{*}_{ijkg}}{\sum_{ijk} \sum_{g=1}^{150} \chi_g\, \Phi^{*}_{ijkg}} \tag{3}$$

where χ_g is the fission spectrum at energy group g and Φ^{*}_{ijkg} the adjoint flux at the FA layer (i,j,k) at energy group g. Thereafter, these weighting functions were averaged over the two symmetric detectors to relieve the effect of core radial position on the detector response. In the MCNP5 150-group adjoint calculations, the neutron microscopic cross-sections for 150 neutron energy groups from the ENDF/B-VII.0 library were used.

To simulate the rod drop experiments, it is expected that a set of the spatial weighting functions insensitive to the control rods position can be generated. On that account, the Assembly Weighting Functions (AWFs) and Axial Weighting Functions (also called the Shape Annealing Functions or SAFs) at RCP and at G1IN, G2IN, or G3IN were determined and inter-compared so as to select an appropriate set of the spatial weighting functions for the dynamic rod worth simulation. The reason for the evaluation of the AWFs and SAFs instead of the three-dimensional weighting functions generated using Eq. (3) is explained as follows.

Because the three-dimensional spatial weighting functions were calculated using MCNP5 and a very large number of FA layers were considered herein (1784 x 10 = 17840 layers), it is not intuitive and extremely time-consuming to compare these weighting functions (17840 values for each set of weighting functions) at different control rod positions, such as at RCP and G1IN. Instead, the AWFs and SAFs at RCP and at G1IN, G2IN, or G3IN, were determined and inter-compared.

The AWF for the FA (i,j) which represents the detector response contributions from individual FAs is calculated by Eq. (4).

$$\omega_{ij} = \sum_{k} \omega_{ijk} \tag{4}$$

The SAF for the core layer (k) which represents the relative importance of core axial position to the detector response is calculated by Eq. (5).

$$\omega_{k} = \sum_{ij} \omega_{ijk} \tag{5}$$

III. RESULTS AND DISCUSSION

The AWFs for the excore detector at RCP were illustrated in Fig. 2. The relative differences of AWFs at RCP and at G1IN, G2IN, or G3IN were provided in Figs. 3-5. The SAFs at RCP and G1IN, G2IN, or G3IN were shown and compared in Figs. 6-8. It is noted that all the spatial weighting functions were obtained, in this study, with a relative error (fractional standard deviation) of less than ~0.035 (3.5%), provided the number of histories to be run in the MCNP5 calculations of a billion.

Fig. 2 signifies that the contributions from the internal fuel assemblies or distant ones must be taken into account for an accurate prediction of the detector response. It can be seen that the weighting function decreased from the outermost fuel assemblies close to the detector towards the innermost fuel assemblies or those located further from the detector; for instance, it was reduced about one order after ~10 layers of fuel assemblies.

From Figs. 3-5, it can be found that the relative difference between AWFs at RCP and at G1IN, G2IN, or G3IN was on average less than ~2.5% for the outer fuel assemblies or those close to the detector whereas it could reach up to ~22/39/49% for a few inner assemblies located near the dropped control rods (G1IN/G2IN/G3IN, respectively). However, such difference of at most ~22/39/49% can be practically neglected in the calculation of the detector response because the detector response contributions from these inner assemblies near the dropped control rods were at least about one order smaller than those from the assemblies located near the excore detector (see Fig. 2).

Figs. 6-8 show that the SAFs have a bottom-peaked shape because the two symmetric detectors were axially located just ~10 cm above the active core bottom (the length of excore detector is 40 cm whereas the active core height is ~82.144 cm). As is seen in those figures, the SAF at RCP slightly overestimates that at G1IN/G2IN/G3IN for the core axial position below RCP and vice versa for the core axial position above RCP. Generally, the relative difference of SAFs at RCP and at G1IN, G2IN, or G3IN was within at most 1.8% and can be neglected.

Hence, it was practically considered that the spatial weighting functions are relatively insensitive to the control rods position during the rod drop experiments and those values at RCP can be applied in the dynamic rod worth simulation for the BFS-76-1A.

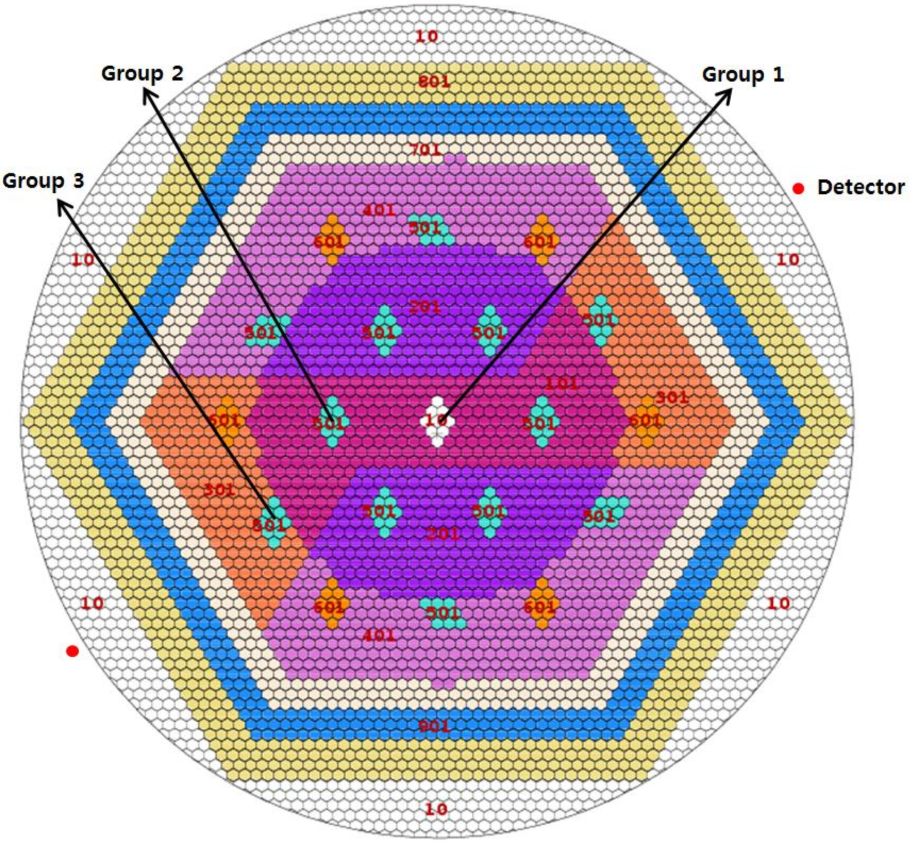


Fig. 1. BFS-76-1A radial core layout

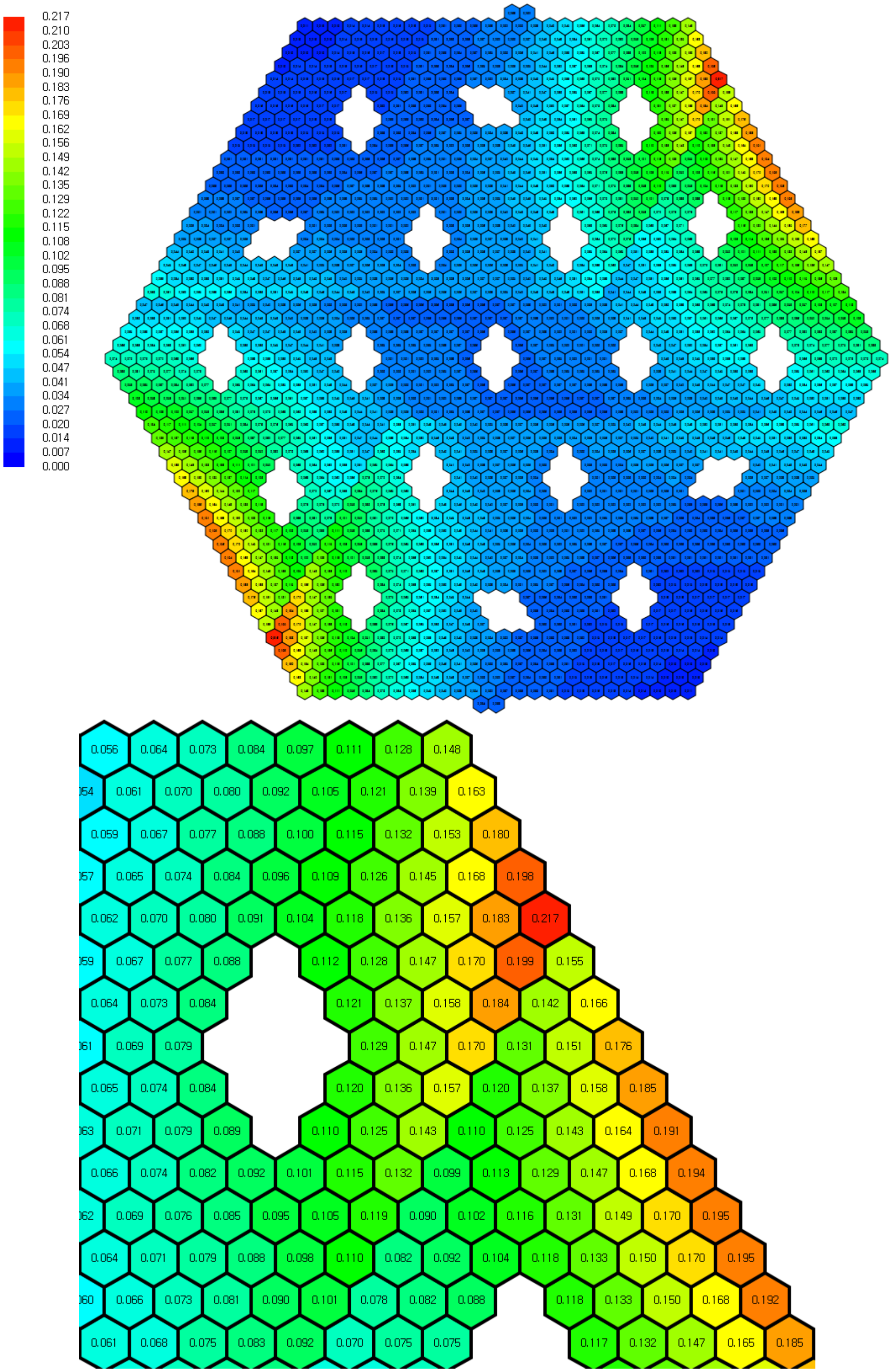
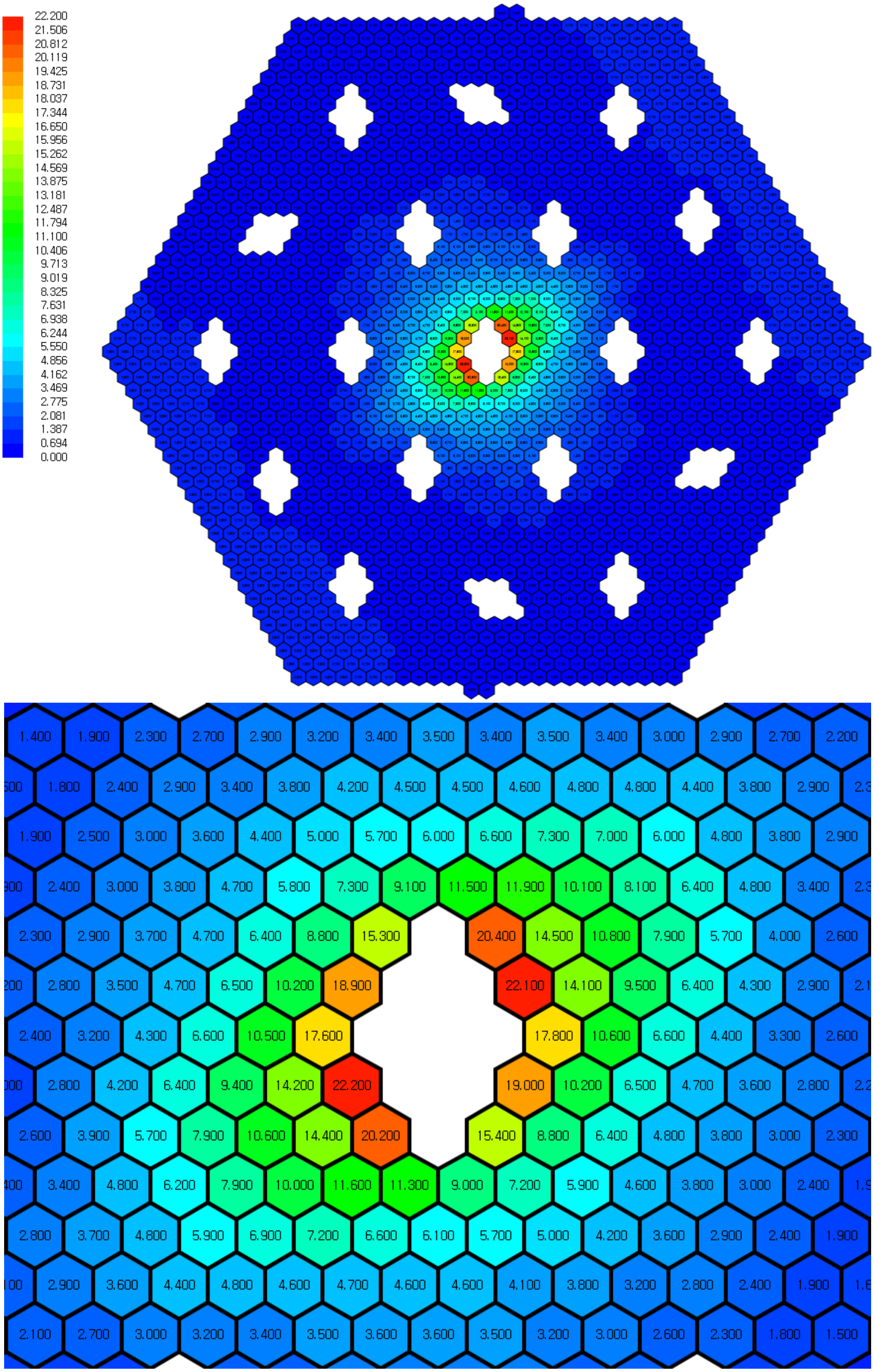


Fig. 2. AWFs at RCP (up) and a partial zoom-in (down), x10^{-2}



1.400 1.900 2.300 2.700 2.900 3.200 3.400 3.500 3.400 3.500 3.400 3.000 2.900 2.700 2.200
500 1.800 2.400 2.900 3.400 3.800 4.200 4.500 4.500 4.600 4.800 4.800 4.400 3.800 2.900 2.3
1.900 2.500 3.000 3.600 4.400 5.000 5.700 6.000 6.600 7.300 7.000 6.000 4.800 3.800 2.900
300 2.400 3.000 3.800 4.700 5.800 7.300 9.100 11.500 11.900 10.100 8.100 6.400 4.800 3.400 2.3
2.300 2.900 3.700 4.700 6.400 8.800 15.300 20.400 14.500 10.800 7.900 5.700 4.000 2.600
200 2.800 3.500 4.700 6.500 10.200 18.900 22.100 14.100 9.500 6.400 4.300 2.900 2.1
2.400 3.200 4.300 6.600 10.500 17.600 17.800 10.600 6.600 4.400 3.300 2.600
000 2.800 4.200 6.400 9.400 14.200 22.200 19.000 10.200 6.500 4.700 3.600 2.800 2.2
2.600 3.900 5.700 7.900 10.600 14.400 20.200 15.400 8.800 6.400 4.800 3.800 3.000 2.300
400 3.400 4.800 6.200 7.900 10.000 11.600 11.300 9.000 7.200 5.900 4.600 3.800 3.000 2.400 1.9
2.800 3.700 4.800 5.900 6.900 7.200 6.600 6.100 5.700 5.000 4.200 3.600 2.900 2.400 1.900
00 2.900 3.600 4.400 4.800 4.600 4.700 4.600 4.600 4.100 3.800 3.200 2.800 2.400 1.900 1.6
2.100 2.700 3.000 3.200 3.400 3.500 3.600 3.600 3.500 3.200 3.000 2.600 2.300 1.800 1.500

Fig. 3. Relative difference of AWFs at RCP and G1IN (up) and a partial zoom-in (down), %

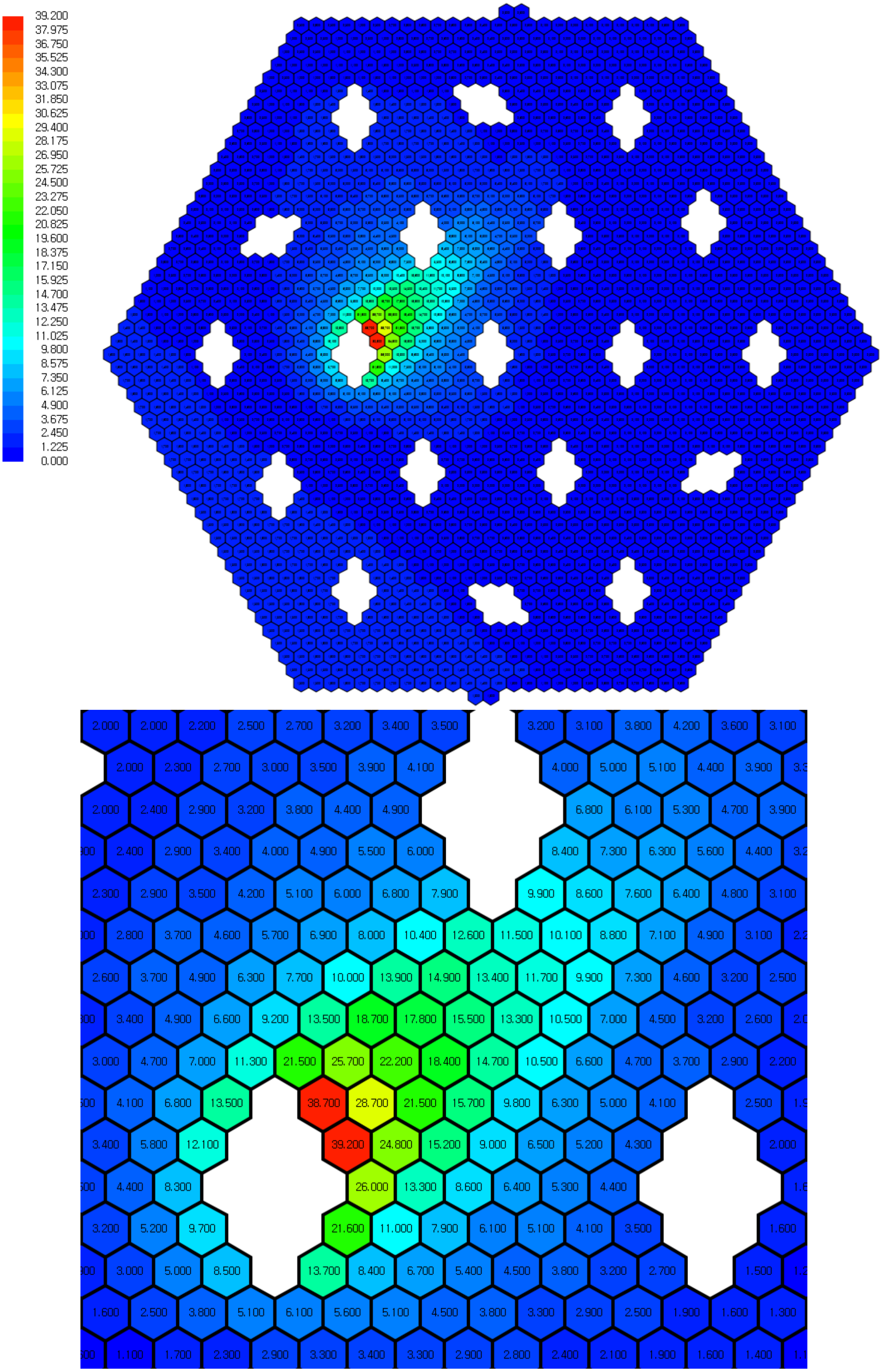


Fig. 4. Relative difference of AWFs at RCP and G2IN (up) and a partial zoom-in (down), %

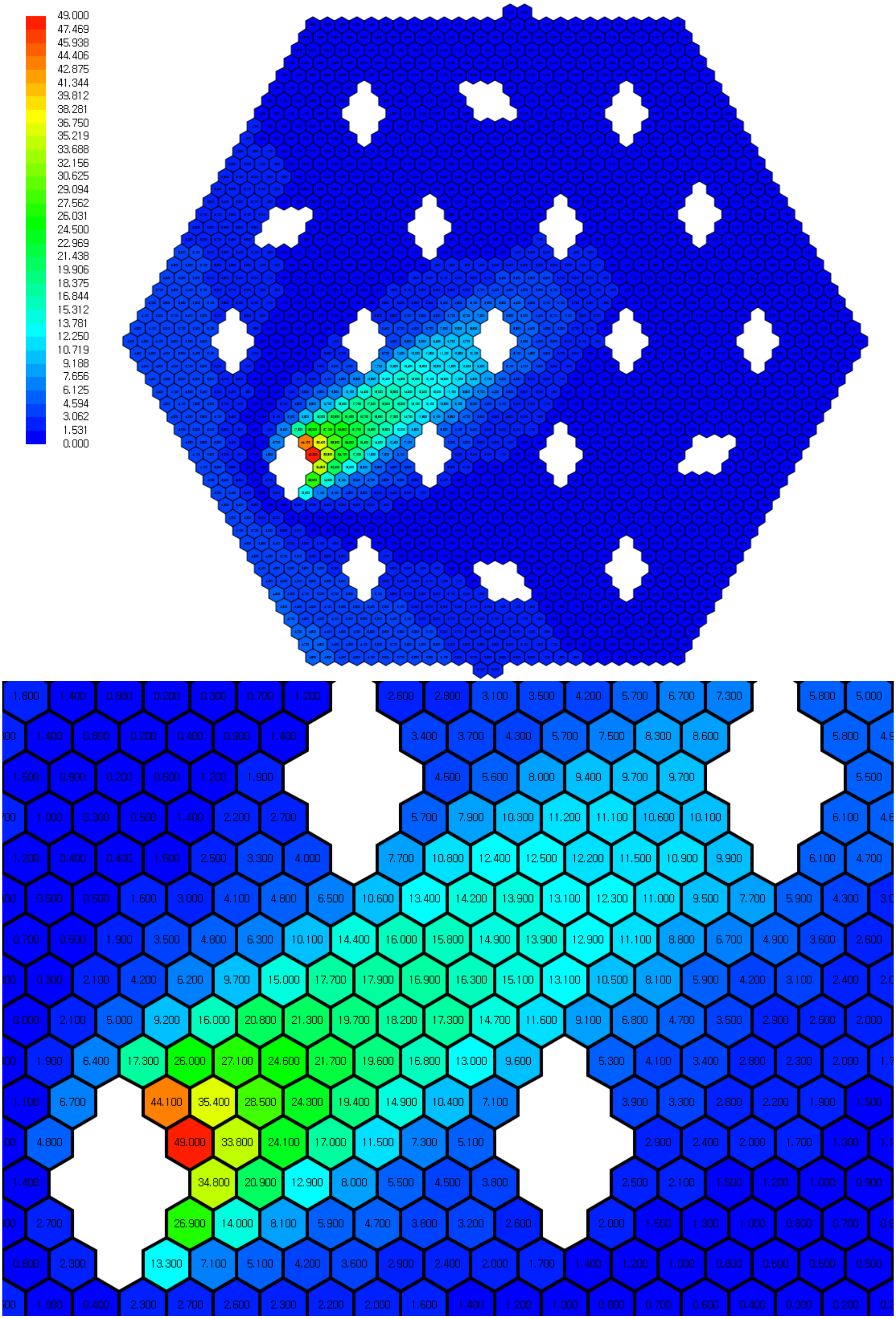


Fig. 5. Relative difference of AWFs at RCP and G3IN (up) and a partial zoom-in (down), %

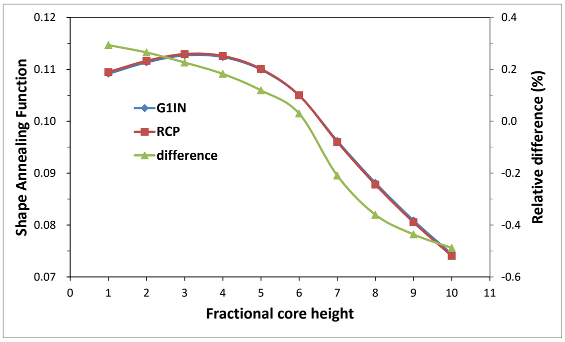


Fig. 6. SAFs at RCP and G1IN and their relative difference (%)

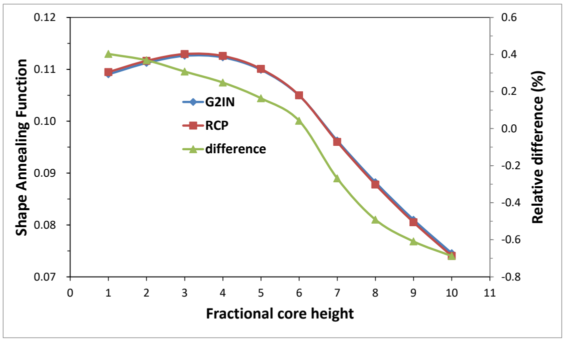


Fig. 7. SAFs at RCP and G2IN and their relative difference (%)

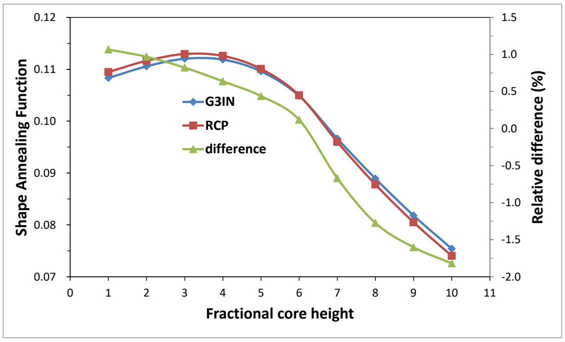


Fig. 8. SAFs at RCP and G3IN and their relative difference (%)

IV. CONCLUSIONS

The excore detector spatial weighting functions for the BFS-76-1A were generated using the MCNP5 150-group adjoint calculations and evaluated in this study. For generation of the weighting functions, all fuel assemblies were taken into account and each of them was divided into ten horizontal layers. To choose an appropriate set of the spatial weighting functions for further use in the dynamic rod worth simulation for the BFS-76-1A, the assembly weighting functions and the shape annealing functions at RCP (Reactor Critical Point) and at the condition under which one control rod group was fully inserted into the core while other control rods at RCP were determined and inter-compared instead of extremely large numbers of the calculated three-dimensional weighting functions. The results indicate that the weighting functions were relatively insensitive to the control rods position during the rod drop experiments and consequently those weighting values at RCP can be applied in the dynamic rod worth simulation and evaluation for the BFS-76-1A. In future work, a dynamic rod worth simulation study based on those spatial weighting functions will be performed for validating the measured rod worths of the BFS-76-1A.

Finally, this work provides a basis for generation and evaluation of the excore detector spatial weighting functions for a SFR and will be applied for further analysis of the detector response aimed at evaluating the worth of control rods for safety design of the PGSFR and at designing a robust neutron flux/power monitoring system for the PGSFR.

ACKNOWLEGEMENTS

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

REFERENCES

[1]. D. H. Hahn et al., “Advanced SFR Design Concepts and R&D Activities,” *Nuclear Engineering and Technology*, 41(4), 427-446, 2009.

[2]. Y. I. Kim et al., “Preliminary Conceptual Design Report of Gen-IV SFR Demonstration Plant,” KAERI/TR-4335/2011, Korea Atomic Energy Research Institute, 2011.

[3]. J. Chang, “Status of Fast Reactor Technology Development in Korea,” The 45th IAEA TWG-FR Meeting, Beijing, China, June 20-22, 2012.

[4]. H. Joo, “Status of Fast Reactor Technology Development in Korea,” The 46th IAEA TWG-FR Meeting, Vienna, Austria, May 21-24, 2013.

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

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

[7]. T. Berki, "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.

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

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

[10]. J. C. Wagner et al., "MCNP: Multigroup/Adjoint Capabilities," LA-12704, Los Alamos National Laboratory, April 1994.