Transactions of the Korean Nuclear Society Autumn Meeting
Yeosu, Korea, October 25-26, 2018

MC^2-3/TWODANT/DIF3D Analysis for the BFS-76 Sodium Void Worth Measurements

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1. Introduction

In Sodium-cooled Fast Reactors (SFRs), voided sodium can cause large reactivity insertion into the core, so it is considered one of major concerns in SFR safety analysis. The voided sodium prevents neutrons from slowing down. Therefore, neutron spectrum in the reactor core can be hardened, and thus, positive reactivity can be introduced. Meanwhile, neutrons can be easily leaked out of core via the voided regions, and this lead to negative reactivity insertion to the core. The reactivity worth can be either positive or negative according to the location of voided region and the reactor design concept. Since the spectrum transition effect normally strongly appears for the core with hard neutron spectrum, the worth can be easily increased in TRU cores; small beta-effective make the worth even higher in terms of dollar unit. Therefore, an accurate code system for estimating sodium void reactivity worth is essential for optimal reactor core design and for reliable safety analysis.

Korean Atomic Energy Research Institute (KAERI) uses MC^2-3 [1], TWODANT [2], and DIF3D-VARIANT [3] code system for SFR neutronics analysis. In this work, the sodium void worth measurements in the BFS-76 [4] reactor physics experiments are analyzed by MC^2-3/TWODANT/DIF3D aiming to validation of the code system.

2. BFS-76 Sodium Void Worth Measurements

The BFS-76 physics experiment was carried out in the BFS-2 facility of IPPE within the framework of validating an early phase of KAERI's sodium-cooled fast burner reactor concept. The BFS-76 critical assembly is designed as a U/Pu metal-fueled core with two enrichment zones without a blanket. The cylindrical fuel rods of the critical assemblies are arranged in a hexagonal lattice with a pitch of 5.1 cm. The unit fuel cell of the fuel rod consists of several types of cylindrical disks surrounded by a cylindrical tube with an outer diameter of 5.0 as plotted in Fig. 1. There are two reference core configurations in BFS-76, which are so called BFS-76-1 and BFS-76-1A. The sodium void worth measurements were conducted only in the BFS-76-1A configuration. For simplicity, the configuration of BFS-76-1A is called BFS-76 here after. The core loading pattern of BFS-76 is given in Fig. 2 and Table I. There were nine different types of experiment rods in the core. The plutonium rods are arranged as alphabet 'Z' shape and uranium rods are loaded in other zones.

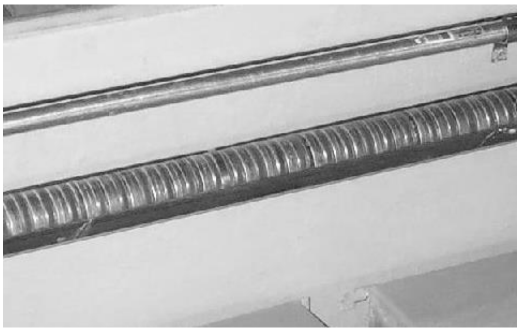

Fig. 1. Cut of a BFS loaded fuel rod

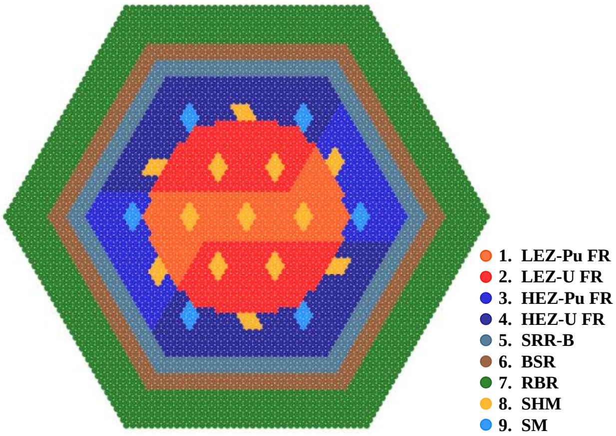

Fig. 2. BFS-76 core loading

Table I. Description of Experiment Rods

No.	Name	Description
1	LEZ-Pu FR	Plutonium fuel rod of low enrichment zone
2	LEZ-U FR	Uranium fuel rod of low enrichment zone
3	HEZ-Pu FR	Plutonium fuel rod of high enrichment zone
4	HEZ-U FR	Uranium fuel rod of high enrichment zone
5	SRR-B	Steel reflector rod filled with blocks
6	BSR	Boron shielding rod
7	RBR	Radial blanket rod
8	SHM	Shim rod mock-up
9	SM	Safety rod mock-up

There were eight steps of sodium void worth measurements in BFS-76, by increasing voided zones from the core center to core periphery including sodium plenums. The voided zones during experiments are plotted in Fig. 3, and the description of each measurement step is given in Table II.

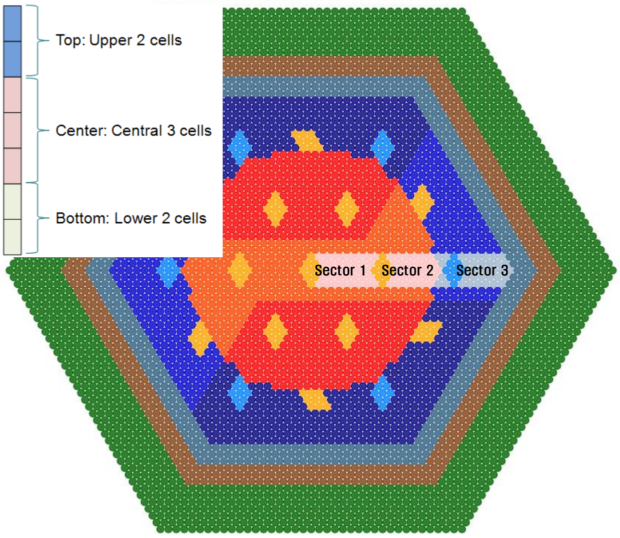

Fig. 3. Sodium void worth measurements in BFS-76

Table II. Voided cells in each step

Step	Description
1	Center 3 core cells in Sector 1
2	Lower 2 core cells in Sector 1
3	Upper 2 core cells in Sector 1
4	Sodium plenum in Sector 1
5	Core cells in Sector 2
6	Sodium plenum in Sector 2
7	Core cells in Sector 3
8	Sodium plenum in Sector 3

The simulation of sodium void is simply substituting sodium discs in fuel rods with empty discs. The height of empty discs is slightly greater than sodium discs, so the axial arrangement is altered after changing discs. The effect of the misalignment is not quantified in this work since the variation of axial boundary is marginal.

3. Estimation of Sodium Void Worth

In this section, the detailed procedure of MC^2-3/ TWODANT/DIF3D modeling is described, and the calculation results are compared to the continuous energy Monte Carlo calculations and measured values.

3.1 MC^2-3/TWODANT/DIF3D Modeling

Basically, the MC^2-3/TWODANT/DIF3D modeling and calculation procedure for sodium void worth measurement experiments are the same as that for control rod worth measurements [5]. The overall calculation is summarized in Fig. 4. The ultra-fine energy group (1041G) cross sections are generated by MC^2-3, and region-wise neutron spectrum is obtained from TWODANT R-Z calculation. The multi-group cross sections are generated via group collapsing according to the neutron spectrum obtained from TWDANT. Finally the whole core transport calculation is performed by DIF3D-VARIANT to obtain flux distribution and multiplication factor.

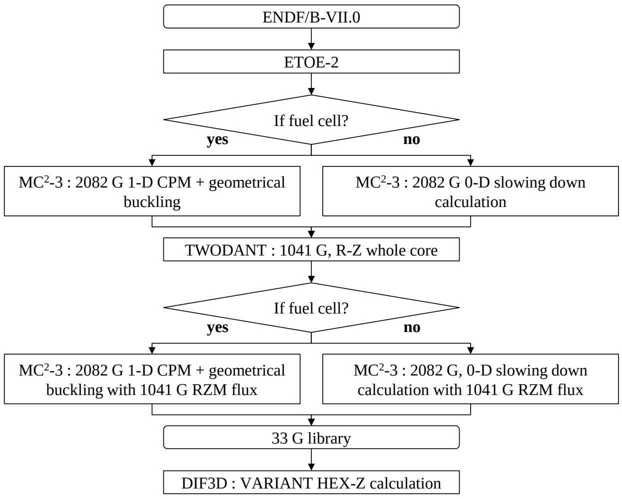

Fig. 4. MC^2-3/TWODANT/DIF3D calculation procedure

In order to prepare multi-group cross sections by MC^2-3, the three-dimensional geometry of disc should be converted to a proper one-dimensional model. Fig. 5 shows typical BFS disc and its one-dimensional model. Since discs are loaded in the tube there exist space between disc and tube. The tube and the void space, called vacancy, are arranged top and bottom of the disc to reflect heterogeneity effect of the tube. Note that the void space is not explicitly modeled in the one-dimensional model since the volume is very small, and less important in transport calculation in slab geometries.

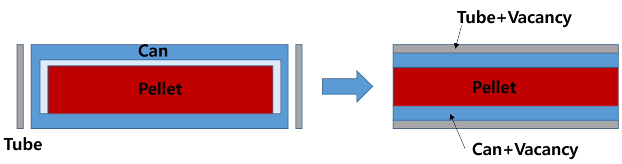

Fig. 5. An example of 1-D model for a fuel disc

The rods in the experiment are defined by repeating some sets of discs, and the set is called unit-cells as plotted in Fig. 6. The multi-group cross sections of unit-cells are directly used in DIF3D-VARIANT calculation. Therefore, several stacks of one-dimensional models of disc forms slab geometry of a unit-cell, and the MC^2-3 calculation is conducted based on the one-dimensional unit-cell models. Note that one-dimensional slowing down calculation in MC^2-3 is only applied to fuel unit-cells while zero-dimensional calculation is conducted for other unit-cells.

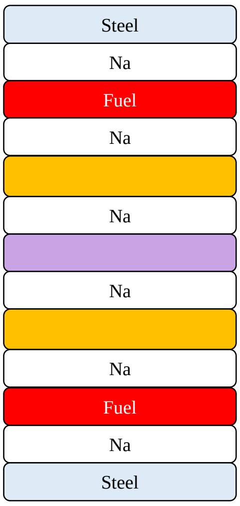

Fig. 6. An example of a unit-cell in BFS-76

The next step is developing TWODANT R-Z models for obtaining region-wise neutron spectrum. Since the core loading pattern is not symmetric, it is not straightforward to make a TWODANT R-Z model. In this work, three different TWODANT R-Z models are generated such that 1) an R-Z core with U fuels, 2) an R-Z core with Pu fuels, and 3) an R-Z core with voided Pu fuels. In this manner, slightly different neutron spectrum between U fuel regions and Pu fuel regions can be reflected during the group collapsing procedure.

The height of each disc is not the same, and this leads to misalignment of axial zones of rods. The difference is minor, but cannot be handled explicitly in DIF3D-VARIANT calculation because of the convergence issues with finer meshes. Additionally, as mentioned before, the height of empty disc is slightly greater than sodium disc and this also introduce misalignment of axial zones. To overcome this, the axial zones are adjusted to have same axial meshes, but the number density of each isotope is adjusted.

3.2 Comparisons with Measured Results

With developed MC^2-3/TWODANT/DIF3D models, the sodium void worth was calculated and compared with MCNP [6] and measured values. Note that ENDF/B-VII.0 [7] data library based calculations were conducted for both MC^2-3 and MCNP. 500,000 neutron histories for 600 active cycles are used in MCNP calculation, which results in standard deviation of 3 pcm for k-eff. The calculation results are summarized in Table III and Fig. 7. Since the core is U/Pu mixed fueled, the measured sodium void worth is around zero. Therefore, the error of sodium void worth is given as Calculation (C) – Experiment (E) instead of C/E. Note that MC^2-3/TWODANT/DIF3D results are appeared as MC^2-3/DIF3D for simplicity.

Table III Sodium Void Worth Calculation Results

Sec.	Voided position	MCNP		MC^2-3/DIF3D
		C-E [pcm]	Std. Dev. [pcm]	C-E [pcm]
1	Core center	1.1	4.4	1.6
	Core bottom	-2.6	5.1	0.3
	Core top	-6	4.4	-2.8
	Sodium plenum	-3.3	4.6	-4.5
2	Core	5.3	4.2	1.5
	Sodium plenum	6	4.8	-1.4
3	Core	-9.2	8.1	5.1
	Sodium plenum	-1.3	4.6	-2.4

The error bars in Fig. 7 includes the measurement uncertainty given by BFS experimenters. MCNP and MC^2-3/DIF3D results show good agreement as those two results are well overlapped with error bars. Also the C-E values are around zero, and overlapped with two-sigma error bars. Therefore, one can conclude that the developed MC^2-3/TWODANT/DIF3D well simulates the sodium void worth measurement experiment in BFS-76.

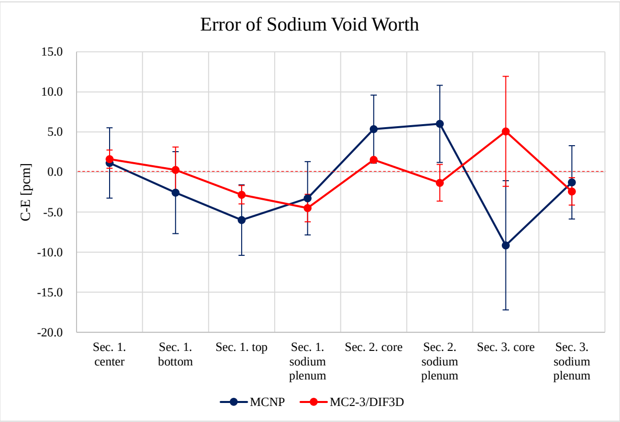

Fig. 7. Error of estimated sodium void worth

The observed errors are much smaller when they are compared to ZPPR-15 sodium void worth measurements [8]. In ZPPR-15 experiments, MC^2-3/DIF3D showed relatively large error especially for small sodium void worth cases. In ZPPR-15 experiment, the plates are loaded axially in to the drawer as plotted in Fig. 8. If a sodium plate is removed to simulate voided sodium, neutrons can easily leak out. However, MC^2-3 slab model cannot reflect the axial neutron streaming. This introduces large errors of sodium void worth estimation in ZPPR-15. On the other hand, when the sodium disc in BFS is exchanged to empty disc, neutrons face other structures for axial direction, and those structures prevent neutron streaming. In this manner, the error appeared smaller in BFS-76 experiments.

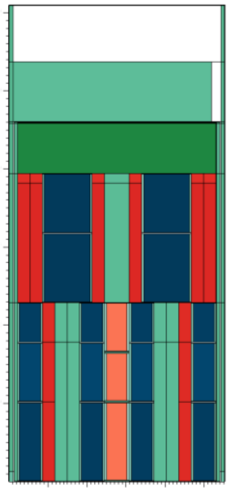

Fig. 8. Typical ZPPR-15 drawer (rod in BFS)

The effect of energy group structures and importance of region-wise neutron spectrum were examined, and the results are summarized in Table IV

Table IV. Sodium Void Worth Calculation Error with Different Calculation Conditions

Sec.	Voided position	C-E [pcm]			
		33G	70G	230G	33G w/ RZ
1	Core center	4.3	3.9	3.2	1.6
	Core bottom	-0.8	-0.8	-0.5	0.3
	Core top	-2.9	-2.7	-2.2	-2.8
	Sodium plenum	-6.3	-5.4	-4.2	-4.5
2	Core	2.3	2.1	2	1.5
	Sodium plenum	-2.6	-2	-1.1	-1.3
3	Core	6.8	6.3	6.5	5.1
	Sodium plenum	-3.4	-3	-2.4	-2.4

According to Table IV, the estimated sodium void worth is not strongly dependent on the energy group structures. This implies that the spectrum hardening effect and also the increased leakage effects can be well captured even with smaller energy groups. Slightly improved results can be obtained when region-wise neutron spectrum from TWODANT R-Z were used, so TWODANT calculation is recommended for sodium void worth estimation.

4. Conclusions

The BFS-76 sodium void worth measurement experiment were analyzed by the MC^2-3/ TWODANT/DIF3D code system, and the calculation results showed good agreement with continuous energy MCNP calculations and measured values. In BFS-76 experiment, the axial neutron streaming after sodium void is not severe, the developed models showed relative accurate results compared to ZPPR-15 experiments.

With some parametric study proves that the number of energy group effect is negligible, so the 33 energy group is good enough for the analysis. The TWODANT calculation can be a hassle in this analysis since the core is not symmetric, but it is recommended as improved calculation results can be obtained.

Even though MC^2-3/TWODANT/DIF3D code system is well validated for the sodium void worth estimation by BFS-76 experiments, more validation efforts might be required especially for strong neutron streaming cases.

ACKNOWLEDGEMENTS

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

REFERENCES

[1] C. H. Lee and W. S. Yang, MC^2-3:Multigroup Cross Section Generation Code for Fast Reactor Analysis, ANL/NE-11-41 Rev.2, Argonne National Laboratory, 2013

[2] R. E. Alcouffe, et.al., User's Guide for TWODANT: A Code Package for Two-Dimensional, Diffusion-Accelerated, Neutral-Particle Transport, LA-10049-M, Los Alamos National Laboratory, 1990.

[3] M. A. Smith, et. al., DIF3D-VARIANT 11.0: A Decade of Updates, ANL/NE-14/1, Argonne National Laboratory, 2014.

[4] M. Semenov, et. al., BFS-76 Assemblies: Model of Korean Advance Sodium Cooled Fast Reactor, IPPE, 2014.

[5] M. J. Lee, S. Yun and J. Y. Lim, Validation of the MC^2-3/TWODANT/DIF3D Code System for Control Rod Worth in BFS-76 Physics Experiments. PHYSOR2018, Cancun, Mexico, 2018.

[6] D. Pelowitz, MCNP6 User's Manual Version 1.0, LA-CP-13-00634, May 2013

[7] M. B. Chadwick, et. al., "ENDF/B-VII.0: Next Generation Evaluated Nuclear Data Library for Nuclear Science and Technology," Nuclear Data Sheets, Vol. 107, p. 2931, 2006.

[8] M. A. Smith, R. M Lell, and C. Lee, MC^2-3 / DIF3D Analysis for the ZPPR-15 Doppler and Sodium Void Worth Measurements, M&C2015, Nashville, TN, United States, 2015.