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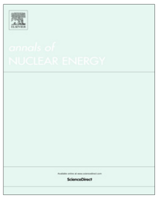

Validation of the MC^2-3/TWODANT/DIF3D code system for control rod worth via BFS-75-1 and BFS-109-2A reactor physics experiments

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ABSTRACT

In this paper, validation of the MC^2-3/TWODANT/DIF3D code system with the ENDF/B-VII.0 library was performed based on two different physics experiments: BFS-75-1 and BFS-109-2A critical assemblies. Both the BFS-75-1 and BFS-109-2A physics experiments were carried out in the Russian BFS facility with collaboration between KAERI and IPPE. The BFS-75-1 critical assembly is a metal-fueled core surrounded by a depleted uranium blanket, and the BFS-109-2A critical assembly is a metal-fueled core surrounded by a steel reflector and sodium/gas plenums. The results of the multi-group MC^2-3/TWODANT/DF3D code were compared with experiments and results of the continuous energy as-built MCNP code.

The MC^2-3/TWODANT/DIF3D model showed excellent agreement with experiments in the reference criticality, i.e., a 70 pcm difference at the maximum. The MC^2-3/TWODANT/DIF3D models estimated the absorber or control rod worth to be between a −6.2% and 8.6% error range vs. that of the experiments.

A remarkable spatial spectrum transition effect was reported, especially for the BFS-109-2A critical assembly, and the TWODANT procedure successfully mitigated this effect by applying a global neutron spectrum during energy group condensation in MC^2-3.

1. Introduction

To validate core neutronics design and related safety parameters for an innovative reactor, uncertainty quantification for nuclear data—i.e., cross-sections—is an essential work. Many studies have been performed to quantify uncertainty induced by the cross-section based on the sensitivity and uncertainty methodology (Cacuci, 2003) using both deterministic (Kodeli, 2000; Rearden, 2006) and Monte Carlo methods (Shim and Kim, 2011; Lee and Shim, 2015). However, the expected uncertainty for the innovative reactor such as the KALIMER-600 reactor (Hahn et al., 2007) might be overestimated compared with other measured data in physics experiments (Rochman et al., 2011; Manturov et al., 2013a,b). Hence, because of the limitation in up-to-date evaluated cross-section covariance data, an integral experiment can be considered as an alternative to validate the core neutronics design and related safety parameters (Salvatores et al., 2013).

The BFS-75-1 physics experiment was carried out in the BFS-1 facility of IPPE in Russia within the framework of validating an early phase of KAERI's KALIMER-150 design in 1997 (Song et al., 2001). A Monte Carlo model of the BFS-75-1 physics experiment has been developed (Yoo et al., 2011). However, owing to incomplete information for the BFS-75-1 experiments, Monte Carlo models have been generated for the reference criticality and sodium void reactivity measurements with disk-wise homogenized models.

Recently, KAERI performed another physics experiment, BFS-109-2A, by collaborating with Russian IPPE in 2012 (Yun et al., 2017); BFS-109-2A comprises the mock-up physics experiments for the 100 MWe metal-fueled uranium core. During the review process of the experimental report of the BFS-109-2A physics experiments, valuable information for the BFS-1 facility, which can also be used for the BFS-75-1 experiments, was discovered. Hence, the previous MCNP models (Pelowitz et al., 2013) were updated as as-built models, and additional loading models were built for the absorber rod.

In addition, deterministic models were built for the purpose of validating KAERI's neutronics design code, the MC^2-3/TWODANT/DIF3D code (Lee and Yang, 2013; Smith et al., 2014). The MC^2-3 code provides 33 group homogenized cross-section based on Ultra Fine Group (UFG) 1-D Collision Probability Method (CPM) calculation and spatial spectrum transition provided by the TWODANT code. The DIF3D code calculates a 3-D hexagonal whole-core problem using the generated 33 group cross-section. The established

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models were validated based on the ENDF/B-VII.0 cross-section library (Chadwick et al., 2006).

Although both the BFS-75-1 and the BFS-109-2A are physics experiments for metal uranium-fueled core, there are noticeable differences between them: the existence of the blanket and sodium/gas plenum. Hence, a comparison of the core characteristics between the two different physics experiments is an interesting study to investigate the boundary effect in the metal-fueled core. Therefore, in this paper, a comparison of the calculation results using both the MCNP and MC^2-3/TWODANT/DIF3D codes with experiments for the reference criticalities and control or absorber rod worth results is presented.

2. Description of the BFS physics experiments

2.1. The BFS-75-1 critical assembly

The BFS-75-1 critical assembly is a uranium metal-fueled core with two enrichment zones surrounded by a depleted uranium blanket. The inner core of the BFS-75-1 critical assembly is composed of 15.11 wt% U-Zr LEZ (Low Enriched Zone), and the outer core is composed of 19.96 wt% U-Zr HEZ (High Enriched Zone) as shown in Fig. 1. The volumetric average enrichment of the core is 18.5 wt%. The cylindrical fuel rods of the critical assemblies are arranged into 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 cm. RB1 represents radial blanket region 1, which is composed of metal uranium (~0.4 wt% enrichment), and RB2 represents radial blanket region 2, which is composed of depleted UO$_2$ (~0.4 wt% enrichment). In each region, 0.4 cm radius steel stick rods are inserted to satisfy the steel volume fraction. A fuel experimental rod is composed of eight fuel unit cells surrounded by a lower axial blanket and upper axial blanket.

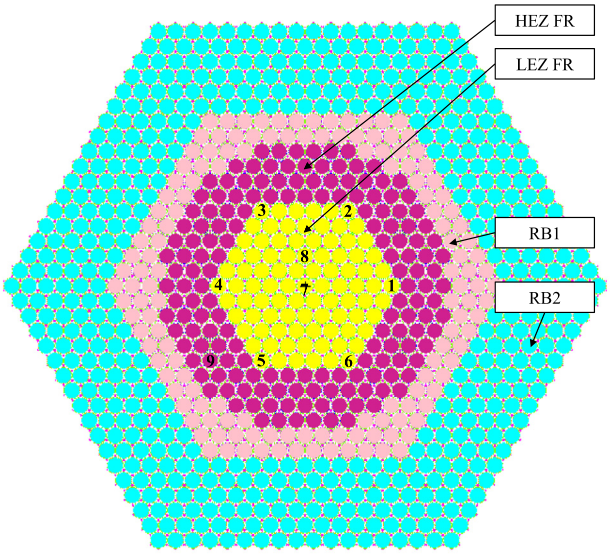

Fig. 1. Configuration of BFS-75-1 critical assembly.

Table 1
Types of absorber rods used in the BFS-75-1 physics experiments.

Type	Description
A	Na disks (33%), Steel disks (33%), and natural B$_4$C disks (34%)
B	80 wt% enriched B$_4$C disks
C	Natural B$_4$C disks (~50%) and Na disks (~50%)
D	Natural B$_4$C disks
E	Na disks (67%) and steel disks (33%)

Table 1 shows the types of absorber rods tested in the BFS-75-1 reactor physics experiment, and Table 2 lists the loading number for the configuration of absorber rod worth measurement in the BFS-75-1 reactor physics experiment. The absorber rod positions are described in Fig. 1. Detailed information about the geometry is in the reference (Song et al., 2001).

2.2. The BFS-109-2A critical assembly

The BFS-109-2A critical assembly is a uranium metal-fueled core with single enrichment zones surrounded by a steel reflector. Fig. 2 shows a radial layout of the BFS-109-2A critical reference model, and Fig. 3 shows an axial layout of the BFS-109-2A critical reference model. In the core model, thirteen mock-up absorber rods (whose positions are from A to M) are placed to measure the absorber rod worth with respect to the distance from the steel reflector.

The core is composed of 18.4 wt% U-Zr FR (Fuel Rod), SRR (Steel Radial Reflector), BSR (Boron Shield Rod), and RRR (Radial Reflector Rod) regions. CPS C/P represents the mock-up absorber rod region. Unlike the BFS-75-1 physics experiment, steel sticks are not inserted into the whole configuration. The critical assembly is placed inside a cylindrical steel vessel. On one side, the cylindrical core vessel is cut by an aluminum wall, and a graphite thermal column is placed behind the wall. On the opposite side of the core is the metal column. Axially, the steel lower reflector is positioned below the core, and sodium plenum and gas plenum are placed above the core.

Table 3 shows the loading number for the configuration of the absorber rod worth measurement in the BFS-109-2A reactor physics experiment. The rod type CPS-EM represents the absorber rod with natural boron, and rod type CPS-M represents the sleeve rod type. The configuration of the absorber unit cell and sleeve unit cell used for the absorber rod and sleeve rod, respectively, will be shown in the next subsection 2.3. The CPS-EM or CPS-M rod is removed from the core in the rod-out stage, and the CPS-EM or CPS-M rod is inserted into the core in the rod-in stage. Hence, a large vacancy exists at the CPS-EM or CPS-M rod position, especially for the rod-out stage.

Table 2
Loadings for the BFS-75-1 absorber rod worth.

Loading number	Absorber rod type	Measured rod position
L000	Critical reference	
L101	A	1
L102	A	2
L103	A	3
L104	A	4
L105	A	5
L106	A	6
L107	A	1, 4
L108	A	1, 3, 5
L109	A	1, 2, 3, 4, 5, 6
L110	C	7
L111	C	8
L112	C	7, 8
L113	D	7
L114	D	8
L115	D	9
L116	A	7
L117	B	7
L118	E	7

In SFRs, not in experimental facilities, sodium occupies the spaces below the control rod at rod-out stage. Then, at rod-in stage, sodium is replaced to the control rod. Hence, it can be said that the