Comparison of Fuel Axial Expansion Characteristics between the BFS-109-2A Experiment Model and the Target Uranium Core Model

Sunghwan Yun* and Sang Ji Kim
Korea Atomic Energy Research Institute (KAERI)
989-111 Daedeok-daero, Yuseong-gu, Daejeon, Korea, 305-353
**Corresponding author: syun@kaeri.re.kr*

1. Introduction

The Korea Atomic Energy Research Institute (KAERI) has been developing a metallic fueled blanket-free SFR design to aim at specific design approval of Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR) up to 2020 [1].

For a metal fueled SFR, the negative reactivity feedback due to thermal expansion of the fuel has been known as a principal safety mechanism to guarantee passive shutdown of the reactor after undercooling accidents [2]. Nevertheless, the inherent safety characteristics by the fuel expansion effect in the PGSFR are still doubtable because the physics experiments for metallic fueled SFR cores with blanket-free concept are scarce in the world. Hence, to validate the thermal expansion effect in the metal fueled blanket-free core, measurements of the fuel expansion reactivity were performed during the BFS-109-2A reactor physics experiment in the Russian BFS-1 critical assembly [3].

The BFS-1 critical assembly is assembled by hundreds of tightly coupled experimental rods in which several types of cylindrical disks were filled, whereas the target uranium core is assembled by dozens of subassemblies composed of fuel rods, sodium coolant, and steel duct. Therefore, assessment of a similarity between the critical assembly and target core is an essential work.

Many researches have been performed to confirm the similarity between critical experiment and real reactor [4, 5, 6, 7] based on the sensitivity and covariance matrix of the isotopes. However, the conventional method for a similarity assessment does not reflect a direct leakage effect and absent isotope effect, which is one of important effects in the fuel expansion phenomenon.

Therefore, in this paper, the direct reactivity decomposition method [8, 9], in which direct leakage and absent isotope effect is embedded, was selected to confirm similarity between a BFS-109-2A experimental model and a target uranium fueled core model for the fuel expansion phenomenon.

2. Models for Critical Assembly and Target Core

The BFS-109-2A is the reactor physics experiment specified for the measurement of steel reflector effect to the reference core and variously positioned control rod worths. The reference U-10Zr loaded core, shown in Figs. 1 and 2, is configured based on the early stage design of the initial PGSFR core [10].

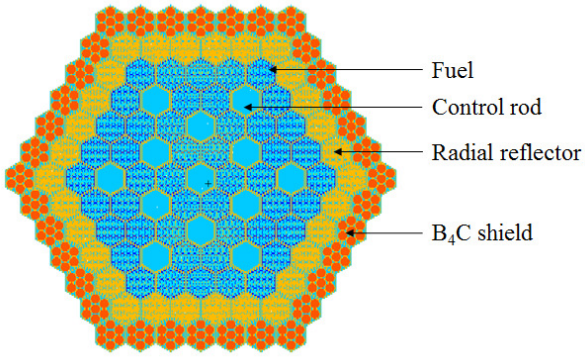

Fig. 1. Radial layout of the target uranium core

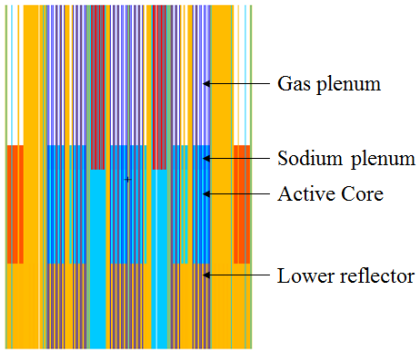

Fig. 2. Axial layout of the target uranium core

The BFS-109-2A critical assemblies are configured with hundreds of fuel rods, boron shield rods, UO_2 radial reflector rods, steel rods, and mock-up control rods as shown in Fig. 3. Each rod is composed of several types of cells such as fuel cell, sodium plenum cell, and gas plenum cells as shown in Fig. 4.

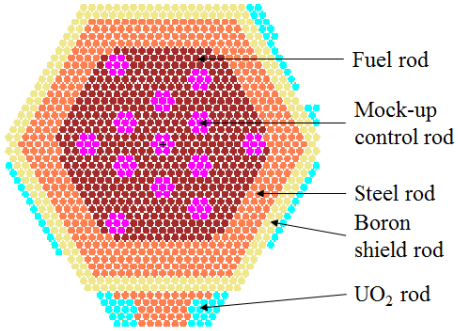

Fig. 3. Radial layout of the BFS-109-2A critical assembly

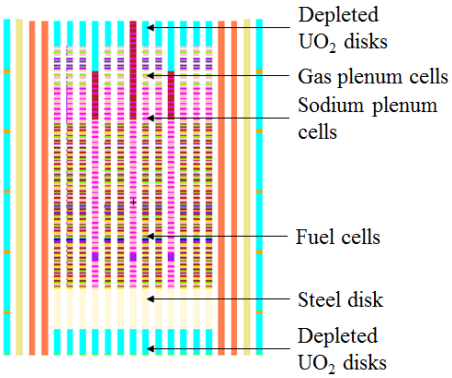

Fig. 4. Axial layout of the BFS-109-2A critical assembly

To model the axial expansion effect of the target core, an approximated expansion model is considered. As shown in Fig. 4, the original fuel cell is changed to the modified fuel cell including ring disk.

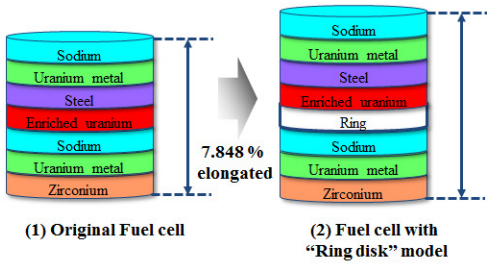

Fig. 5. Axial expansion model in the BFS-109-2A

3. Direct Reactivity Decomposition Method

In the direct reactivity decomposition method, reactivity is derived from following neutron transport equation:

$$\begin{aligned}&\vec{\Omega}\cdot\nabla\psi(\vec{r},\vec{\Omega},E)+\sigma_t(\vec{r},E)\psi(\vec{r},\vec{\Omega},E)\\&=\int d\vec{\Omega}'\int dE'\sigma_s(\vec{r},E'\to E,\vec{\Omega}'\cdot\vec{\Omega})\psi(\vec{r},\vec{\Omega}',E')\\&+\frac{1}{k_{eff}}\frac{\chi(E)}{4\pi}\int d\vec{\Omega}'\int dE'\nu(\vec{r},E')\sigma_f(\vec{r},E')\psi(\vec{r},\vec{\Omega}',E').\end{aligned}\tag{1}$$

Operating $\iiint d\vec{r}d\vec{\Omega}dE$ to Eq. (1), following simple balance equation is obtained:

$$L+C+F=\frac{1}{k_{eff}}\nu F,\tag{2}$$

where

$$L\equiv\iiint d\vec{r}d\vec{\Omega}dE\;\vec{\Omega}\cdot\nabla\psi(\vec{r},\vec{\Omega},E),\tag{3}$$

$$F\equiv\int d\vec{r}\int dE'\sigma_f(\vec{r},E')\int d\vec{\Omega}'\psi(\vec{r},\vec{\Omega}',E'),\tag{4}$$

$$\nu\equiv\frac{\int d\vec{r}\int dE'\nu(\vec{r},E')\sigma_f(\vec{r},E')\int d\vec{\Omega}'\psi(\vec{r},\vec{\Omega}',E')}{\int d\vec{r}\int dE'\sigma_f(\vec{r},E')\int d\vec{\Omega}'\psi(\vec{r},\vec{\Omega}',E')},\tag{5}$$

$$\begin{aligned}C\equiv&\iiint d\vec{r}d\vec{\Omega}dE\\&\left(\begin{array}{l}\left(\begin{array}{l}\sigma_c(\vec{r},E)+\sigma_f(\vec{r},E)\\+\int d\vec{\Omega}'\int dE'\sigma_s(\vec{r},E\to E',\vec{\Omega}\cdot\vec{\Omega}')\end{array}\right)\psi(\vec{r},\vec{\Omega},E)\\-\int d\vec{\Omega}'\int dE'\sigma_s(\vec{r},E'\to E,\vec{\Omega}'\cdot\vec{\Omega})\psi(\vec{r},\vec{\Omega}',E')\\-\frac{\chi(E)}{4\pi}\int d\vec{\Omega}'\int dE'\sigma_f(\vec{r},E')\psi(\vec{r},\vec{\Omega}',E')\end{array}\right)\\=&\iiint d\vec{r}d\vec{\Omega}dE\sigma_c(\vec{r},E)\psi(\vec{r},\vec{\Omega},E).\end{aligned}\tag{6}$$

The reactivity can be expressed using parameters defined at Eq. (2) as:

$$\rho=1-\frac{1}{k_{eff}}=1-\frac{L+C+F}{\nu F}.\tag{7}$$

Eq. (7) can be re-written by the first-order Taylor series expansion as [11]:

$$\begin{aligned}\rho_2\cong\rho_1&+\left(\frac{\partial\rho}{\partial L}\right)_1(L_2-L_1)+\left(\frac{\partial\rho}{\partial C}\right)_1(C_2-C_1)\\&+\left(\frac{\partial\rho}{\partial F}\right)_1(F_2-F_1)+\left(\frac{\partial\rho}{\partial\nu}\right)_1(\nu_2-\nu_1).\end{aligned}\tag{8}$$

The derivation terms in Eq. (8) are derived from Eq. (7) as follows:

$$\frac{\partial\rho}{\partial L}=\frac{\partial\rho}{\partial C}=-\frac{1}{\nu F},\tag{9}$$

$$\begin{aligned}\frac{\partial\rho}{\partial F}&=\frac{\partial}{\partial F}\left(1-\frac{L+C+F}{\nu F}\right)\\&=\frac{1}{\nu F}\left(\frac{\nu}{k_{eff}}-1\right),\end{aligned}\tag{10}$$

$$\begin{aligned}\frac{\partial\rho}{\partial\nu}&=\frac{\partial}{\partial\nu}\left(1-\frac{L+C+F}{\nu F}\right)\\&=\left(\frac{L+C+F}{F}\right)\frac{1}{\nu^2}\\&=\frac{1}{\nu k_{eff}}.\end{aligned}\tag{11}$$

Now, Eq. (8) can be rewritten as:

$$\begin{aligned}\rho_2-\rho_1=&-\frac{1}{\nu_1F_1}(L_2-L_1)-\frac{1}{\nu_1F_1}(C_2-C_1)\\&+\frac{1}{\nu_1F_1}\left(\frac{\nu_1}{k_{eff,1}}-1\right)(F_2-F_1)\\&+\frac{1}{\nu_1k_{eff,1}}(\nu_2-\nu_1).\end{aligned}\tag{12}$$

Every term expressed in Eq. (12) can be obtained by a Monte Carlo tally or deterministic reaction rate calculation.

4. Analysis Results

In this study, the MCNP5 code [12] was used with continuous energy ENDF/B-VII.0 library to omit uncertainties in multi-group cross-section. Fuel rods in the target core model were extended 7.848 % axially, which is the identical expansion rate to the modified fuel cell in the BFS-109-2A model.

Neutron spectrums in the whole problem region for the target core and the critical assembly are shown in Fig. 4 while those in the central core region are shown in Fig. 5.

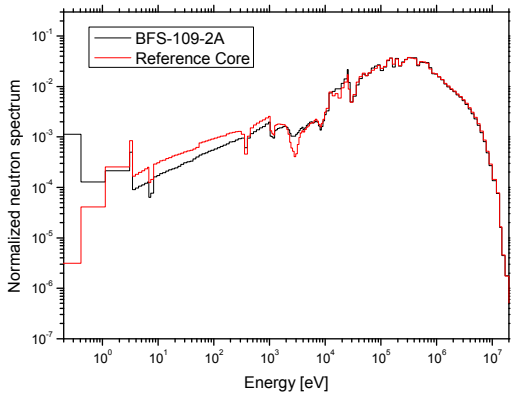

Fig. 4. Neutron spectrums in the whole problem region

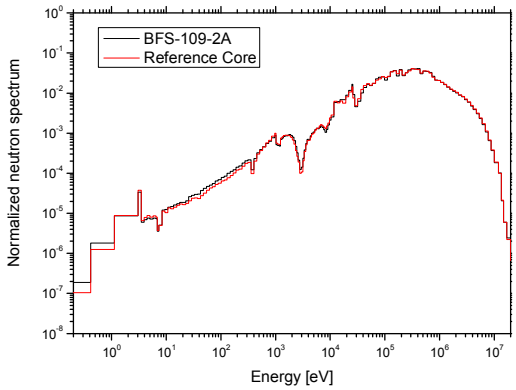

Fig. 5. Neutron spectrums in the central core region

In the central core region, spectrums of two models showed good agreement. However, due to the effect of peripheral depleted UO_2 radial reflector rods and steel rods in the critical assembly model, the critical assembly model showed softened spectrums compared to those of the target core model in the whole problem region.

Total contributions to the reactivity by the axial expansion effect are shown in Table I.

Table I: Decomposed reactivity components in target core and critical assembly model

	Target core model [pcm Δρ]	Critical assembly model [pcm Δρ]
Leakage	-258.30±1.86	-365.04±1.47
Capture	-666.66±2.30	-549.12±1.54
Fission	-1600.79±2.59	-1406.23±1.86
ν	0.00	0.00
Total	-2525.75±3.93	-2320.40±2.83
Direct calculation	-2628.72±5.04	-2395.69±2.91

The direct decomposition method estimated the total axial expansion reactivities within a 4 % error. This error is coming from the first-order Taylor approximation shown in Eq. (8) due to large perturbation such as whole core fuel expansion. Hence, a much smaller error will result in a small perturbation problem such as local fuel expansion as reported in reference [13].

Energy dependent contributions by leakage, capture, and fission are shown in Figs. 5, 6, and 7, respectively.

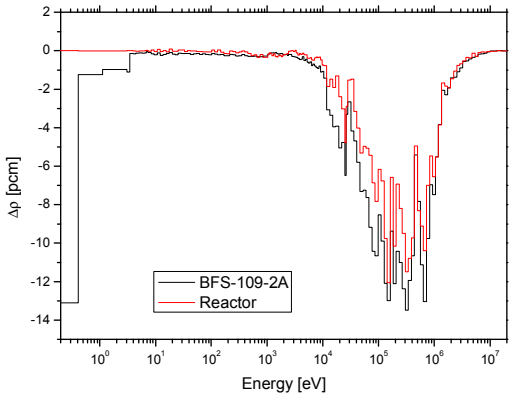

Fig. 6. Leakage rate distributions in the whole problem region

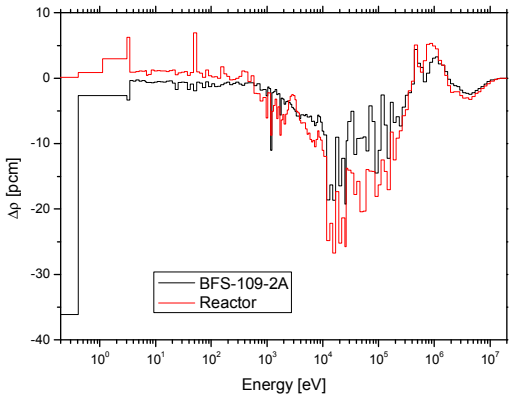

Fig. 7. Capture reaction rate distributions in the whole problem region

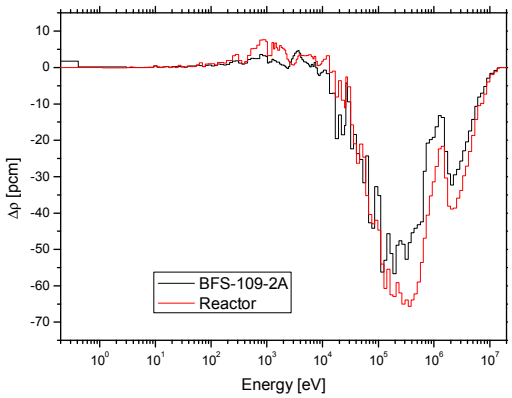

Fig. 8. Fission reaction rate distributions in the whole problem region

In spite of discrepancies in the whole core spectrum, distributions of leakage, capture, and fission components of axial expansion reactivities showed meaningful agreement with each other. However, more negative leakage components in the critical assembly model were observed due to the vacancy between experimental rods, whereas less negative capture and fission components were observed.

3. Conclusions

In this paper, fuel axial expansion characteristics of the uranium target core and the BFS-109-2A critical assembly were analyzed using the direct reactivity decomposition method.

Two models showed meaningful agreement in neutron spectrum at the central region and distributions of leakage, capture, and fission components of axial expansion reactivities. However, energy integrated reactivity components showed considerable discrepancies due to a geometrical difference. Although the final axial expansion reactivities of two models showed a 10 % discrepancy, it is still doubtful to assess the similarity between the two models quantitatively.

Hence, a new assessment method for similarity of two models is proposed in reference [13] by the authors. A quantitative error between two systems can be derived by the proposed assessment method in terms of pcm or cent.

ACKNOWLEDGMENTS

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