History Effect Treatment Methodology in Pin-by-pin Code NECP-Bamboo2.0

Sicheng Wang [a,b*], Liangzhi Cao [a], Yunzhao Li [a], Yonghee Kim [b]
[a] *School of Energy and Power Engineering, Xi'an Jiaotong Univ., 28 West Xianning Rd., Xi'an, Shaanxi 710049, P. R. China*
[b] *Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology., 291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea*
[*] *Corresponding author: sichengwang@kaist.ac.kr*

1. Introduction

The two-step method is widely used in the neutronic analysis of PWR cores, consisting of the 2D lattice calculation to generate the assembly-wise or pin-wise homogenized few-group constants, and the 3D whole-core calculation to obtain the eigenvalue and the power distributions based on the homogenized constants [1]. Considering the unpredictability of the actual operation conditions, the lattice calculation is usually carried out under a series of discrete operating points to obtain the relationship between the few-group constants and the state parameters (SPs), including burnup (BU), moderator temperature (TM), fuel effective temperature (TF), boron concentration (CB) and so on. The relationship would be further functionalized into a continuous relationship, also known as the few-group library or tablet. Cross-sections (XSs) can then be obtained according to the SPs gained from the whole-core multi-physics calculation and the pre-calculated library. This process is called "parameterization", which is one of the important bases to ensure the accuracy of the "two-step" calculation scheme.

According to the conventional parameterization, the XSs used in the whole-core calculation is just related to the instantaneous value of BU and other SPs of each mesh, instead of the certain change process of the SPs. A specific change process of the SPs is defined as a history. Different histories to a certain condition will lead to different nuclide composition variation along with time, and consequently to different fine-group flux and few-group homogenized XSs. The above phenomenon is called the "history effect", which turns out to be a problem that needs to be cogitated in the parameterization process [2]. Currently, several correction methods have been proposed to treat history effects including the micro-depletion methods and the microscopic XS correction methods, which show good results when employed in the simulation of the conventional PWR cores. However, due to the limitation of the methods themself, difficulties are encountered in problems with strong heterogeneity such as the control rod (CR) movement.

The purpose of this paper is to develop an improved microscopic cross-section correction method in NECP-Bamboo2.0, a PWR-core pin-by-pin analysis code system developed by Xi'an Jiaotong University [3]. The improved method consists of a novel lattice calculation structure and a comprehensive macroscopic XS calculation model in the core code. The comparison with the existing methods can confirm the effectiveness and reliability of the new method.

2. Methods

2.1 Macro-depletion and Micro-depletion Methods

Considering the calculation cost and the coverage over whole-core operating conditions, the traditional lattice calculation structure is the Base-Branch structure shown in Fig. 1 [4]. It consists of the "nominal-base" calculation and the "nominal-branch" calculation. The nominal values of all the SPs are firstly selected beforehand according to the designed operating conditions of the PWR core of interest. The nominal-base calculation is then carried out under the combination of the nominal values, which is a depletion calculation in essence. At each nominal-base point, the nuclide number densities and few-group homogenized XSs are obtained. Finally, nominal-branch calculations are performed to generate the homogenized XSs of the branch points, with the instantaneous change of the SPs other than BU from nominal values to off-nominal values while maintaining the nuclide number densities and the value of BU.

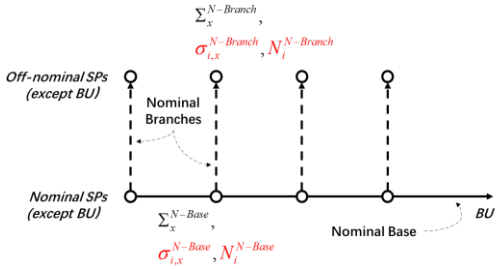


Fig. 1. Diagram of the Base-Branch structure

The XS model used in the core code determines the output of the lattice calculation. When the Macro-depletion model (MAD) is employed, the continuous function $F_\Sigma\left(\overrightarrow{\boldsymbol{SP}}\right)$ between the macroscopic XSs (MacXSs) and SPs is contained in the few-group library. Hence only the MacXSs are required as the output of the lattice calculation. The XSs for the whole-core calculation are obtained by substituting the actual operating conditions $\overrightarrow{\boldsymbol{SP}_{\text{core}}}$ into the few-group library as follows:

$$\Sigma_x^{\text{Lib}} = F_{\Sigma_x}\left(\overrightarrow{\boldsymbol{SP}_{\text{core}}}\right) \tag{1}$$

where the subscript x stands for different reaction branches, the superscript Lib stands for the value obtained from the few-group library.

When the micro-depletion correction method (MID) is employed [5], the additional output of the nuclide number densities $N_i^{\text{N-Base}}, N_i^{\text{N-Branch}}$ and few-group microscopic XSs (MicXSs) $\sigma_{i,x}^{\text{N-Base}}, \sigma_{i,x}^{\text{N-Branch}}$ of the important nuclides are required, where the subscript i stands for the important nuclides. Before the parameterization, the following preprocessing is performed in MID:

$$\Delta\Sigma_x^{\text{N}} = \Sigma_x^{\text{N}} - \sum_i N_i^{\text{N}} \sigma_{i,x}^{\text{N}} \tag{2}$$

where the superscript N stands for the nominal calculations, including nominal-base calculation and nominal-branch calculation, the $\Delta\Sigma$ stands for the remaining term of MacXSs.

$\Delta\Sigma_x^{\text{N}}, \sigma_{i,x}^{\text{N}}$ are parameterized and stored in the few-group library. In the core calculation, the nuclide number densities of important nuclides are firstly updated according to the actual operation history, and then the MacXSs are combined with the microscopic information and the remaining terms of MacXSs obtained from the few-group library:

$$\Sigma_x^{Cal} = \Delta\Sigma_x^{\text{Lib}} + \sum_i N_i^{\text{Cal}} \sigma_{i,x}^{\text{Lib}} \tag{3}$$

where the superscript Cal stands for the value that is calculated from the core code. The modified MacXSs can be used to update the flux distribution. Iterations are then carried out until both the flux and nuclide number densities converge.

The MID partially realizes the treatment of the history effect by considering the influence of actual history on nuclide number densities. However, the MicXSs used in Eq. (3) still ignore the impact of different histories, which will introduce bias.

2.2 Microscopic Cross-section Correction Method

To further consider the effects of different histories on the MicXSs, the Multi-Base structure is introduced for the lattice calculation as shown in Fig. 2. The additional depletion histories under the combinations of off-nominal state parameters are defined as "off-nominal base", hence each condition point can possess two sets of few-group homogenized XSs within the Multi-Base structure.

The number densities of several key nuclides, which are sensitive to different histories, are summed as the characteristic historical quantities HQ. And the relative deviation of the HQ is considered to be proportional to the relative deviation of the XSs to be corrected [6]. According to the above assumption, the MicXSs correction coefficient m is obtained as follows:

$$m_{i,x} = \frac{1}{f}\left(\frac{\sigma_{i,x}^{\text{Off}}}{\sigma_{i,x}^{\text{N}}} - 1\right), \qquad f = \frac{HQ^{\text{Off}}}{HQ^{\text{N}}} - 1, \tag{4}$$
$$HQ = \sum N_{U-235} + N_{Pu-239} + N_{Pu-241}$$

where the superscript Off stands for the value under the off-nominal base; f in the equation is an intermediate variable.

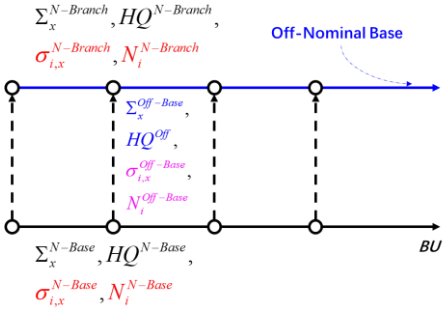


Fig. 2. Diagram of the Multi-Base structure

In the microscopic XS correction method (MIC), $m_{i,x}, HQ^{\text{N}}$ are considered as different kinds of XSs to participate in the parameterization calculation, and the corrected MicXSs shown in Eq. (5) are implemented in the micro-depletion calculation in the core calculation:

$$\sigma_{i,x}^{\text{Cal}} = \sigma_{i,x}^{\text{Lib}} \cdot (m_{i,x}^{\text{Lib}} \cdot f^{\text{Cal}} + 1), \qquad f^{\text{Cal}} = \frac{HQ^{\text{Cal}}}{HQ^{\text{Lib}}} - 1 \tag{5},$$

while the final MacXSs used for the multi-physics calculation can be written as follows:

$$\Sigma_x^{\text{Cal}} = \Delta\Sigma_x^{\text{Lib}} + \sum_i N_i^{\text{Cal}} \cdot \sigma_{i,x}^{\text{Cal}} \tag{6}.$$

2.3 Improved Microscopic Cross-section Correction Method

The MIC has partially added corrections for MicXSs on top of the MID. It can provide a better correction for most of the history effects. However, it should be noted that, according to the Multi-Base structure, there is still only one history simulated for the points belonging to the nominal base, where the values of XS correction coefficients $m_{i,x}$ for the parameterization could only be zero. Hence, a problem named "correction deterioration" could occur in the core calculation, which will worsen the correction result, especially for the CR movement history.

This correction deterioration problem will arise in the depletion points where the SPs happen to be nominal values in the core calculation. For these points, the XS correction coefficients $m_{i,x}^{\text{Lib}}$ obtained from the few-group library are zero, hence the correction term $\left(m_{i,x}^{\text{Lib}} \cdot f^{\text{Cal}} + 1\right)$ in Eq. (5) could have no other value but 1. In this case, the correction formula Eq. (6) of the MIC degenerates to the correction formula Eq. (3) of the MID. This means, essentially, that the effect of the

instantaneous change from the off-nominal base to the nominal base could not be considered. The problem would not be so serious for the history result from CB/TM/TF or other SPs which vary over a continuous interval. However, since the CR has only two discrete values, either with or without a rod, it would lead to a particularly serious deterioration of the correction formula in the history of the CR movement. The impact of this phenomenon must be considered.

In response, a new Bi-direction Branch structure as shown in Fig. 3 is proposed in this paper. If the Multi-Base structure is considered as a supplement to the Base-Branch structure, then the Bi-direction Branch structure is further optimization of the Multi-Base structure. The newly introduced off-nominal-branch calculation, which considers the instantaneous change from the off-nominal base to the nominal base, is added to the Multi-Base calculation. Thus, the non-zero values of the XS correction coefficient at the nominal-base points could be obtained, and the problem of correction deterioration could be overcome consequently.

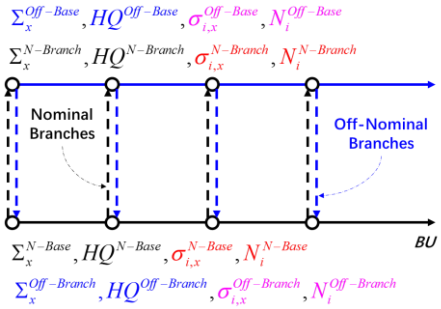


Fig. 3. Diagram of the Bi-direction Branch structure

The improved microscopic XS correction method (IMIC) employs the Bi-direction Branch structure as the lattice calculation structure. Besides, considering that the contribution of non-depleting nuclides, such as hydrogen and oxygen, to the homogenized few-group MacXSs varies under different histories because the nuclide inventory varies differently, a more comprehensive multi-scale XS calculation model is proposed in the core calculation as follows:

$$\Sigma_x^{\mathrm{Cal}} = \Delta\Sigma_x^{\mathrm{Lib}} \cdot (M_{i,x}^{\mathrm{Lib}} \cdot f^{\mathrm{Cal}} + 1) + \sum_i N_i^{\mathrm{Cal}} \cdot \sigma_{i,x}^{\mathrm{Cal}} \qquad (7)$$

where M is the correction coefficient for the remaining term of MacXSs, which shares a similar formula to the MicXSs correction coefficient as follows:

$$M_x = \frac{1}{f}\left(\frac{\Delta\Sigma_x^{\mathrm{Off}}}{\Delta\Sigma_x^{\mathrm{N}}} - 1\right), \qquad f = \frac{HQ^{\mathrm{Off}}}{HQ^{\mathrm{N}}} - 1 \qquad (8).$$

3. Results

3.1 Single-assembly Control Rod Movement History

The history resulting from the Ag-In-Cd (AIC) CR movement based on the single-assembly problem was simulated using NECP-Bamboo2.0 with different correction methods. The layout of the fuel assembly is shown in Fig. 4.

The fuel assembly used for the single-assembly calculation is one with 2.0% enrichment. The variation of the CR position with the depletion is shown in Fig. 5, where the value 1 stands for that the rods are inserted and the value 0 stands for that the rods are withdrawn. The references in this section come from the one-step calculation results of Bamboo-Lattice2.0.

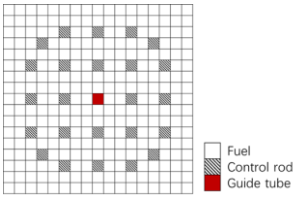


Fig. 4. Diagram of the Bi-direction Branch structure

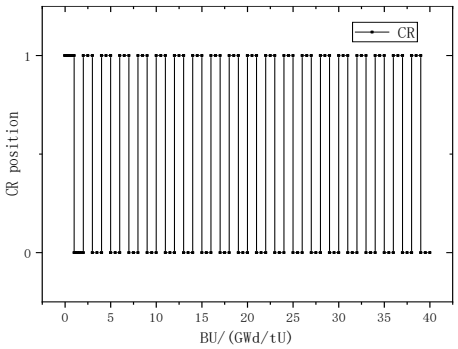


Fig. 5. CR position history

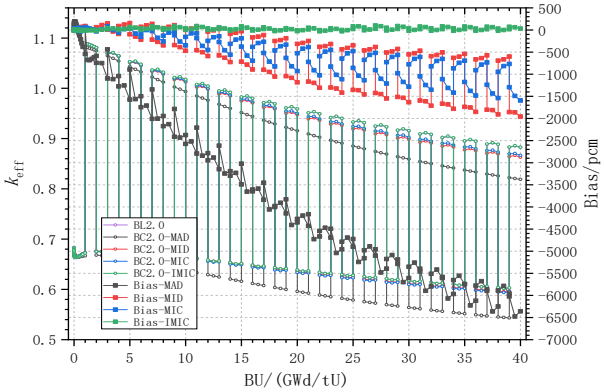


Fig. 6. Bias of k_{eff} for the SA CR movement problem

The k_{eff} values obtained from different correction methods are shown and compared with the reference value in Fig. 6, while the relative bias of pin-wise power distribution compared with the reference value under 40 GWd/tU is shown in Fig. 7. Fig. 6 demonstrates that the value of maximum k_{eff} bias exceeds -6000 pcm at 40 GWd/tU without any correction. With the micro-depletion correction and the microscopic XS correction, the values of maximum k_{eff} bias are -2000pcm and -1500pcm, respectively. Besides, there is an obvious accumulation with depletion for all three methods. It should be noted that the main reason

for the huge bias of the microscopic XS correction is that, due to the lack of the correction for the MicXSs in the nominal base, the bias of nuclide number densities will gradually accumulate in the following depletion process and finally affect the subsequent calculation on both the nominal points and the off-nominal points. Once the improved microscopic XS correction is employed, the correction deterioration is overcome, and the bias can be kept within ±150 pcm and no longer accumulates with the depletion. Fig. 7 demonstrates that the positive results of the pin-wise power distribution could also be obtained by the improved microscopic XS correction. The root mean square (RMS) error is 3.38%, 0.15%, 0.21% and 0.01% for MAD, MID, MIC and IMIC at 40 GWd/tU, respectively.

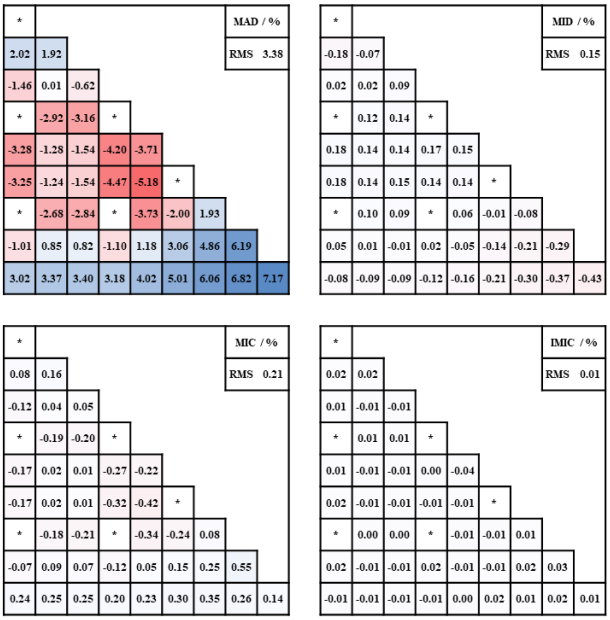


Fig. 7. Relative bias of pin-wise power distribution for the SA CR movement problem

3.2 Multi-assembly Control Rod Movement History

The layout of the multi-assembly problem is shown in Fig. 8. The U enrichment used in the problems is 2.0% and 5.0%. Only the AIC CR belonging to the 2.0% fuel assembly was designed to move for this problem. The variation of the CR position with the depletion is the same as in the single assembly problem. Besides, considering the interaction between assemblies, when the multi-assembly average BU is 40 GWd/tU, the local pin-cell BU could be far beyond 40 GWd/tU, which will lead to a negative influence on the fitting accuracy. Hence the multi-assembly cases were all calculated to 35 GWd/tU to reduce the influence of fitting error on the reliability of the results.

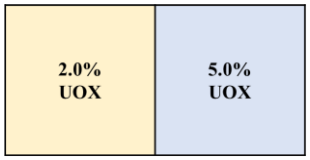


Fig. 8. Layout of the multi-assembly problem

The k_{eff} values obtained from different correction methods are shown and compared with the reference value in Fig. 9, while the bias of pin-wise power distribution compared with the reference value under 15 GWd/tU, 25 GWd/tU, and 35 GWd/tU and shown in Fig. 10 and Tables 1-2. It should be pointed out that since the relative bias of pin-wise power distribution of the macro-depletion method is numerically incompatible, the color bar of the MID, MIC, and IMIC is the same while the color bar of MAD is different from others.

Compared with the single-assembly problem, a main difference of the multi-assembly problem is that the environment needs to be taken into account. The environments are variable and will lead to differences in the spectrum during the depletion process, which could be viewed as another type of history. Fig. 9 demonstrates that for the multi-assembly problem, since the variation of the nuclide number densities at low burnup is not obvious, the accuracy is simply influenced by the difference between the employment of reflective boundary in the lattice calculation and the actual boundary condition in the core calculation. With the deepening of the burnup, both the influence of the environment and the influence of the varying SPs can be uniformly considered in the change of the nuclide number densities. Hence, all the correction methods could be able to show the correction effect on the environment under high burnup, theoretically. Since the improved method has a more comprehensive simulation of the nuclide number densities, the correction effect is most positive. The k_{eff} bias of the improved method under high burnup can be kept within 100 pcm and the RMS of the relative bias of pin-wise power distribution can be kept within 0.5%, while a gradual error accumulation could be obtained by the other methods.

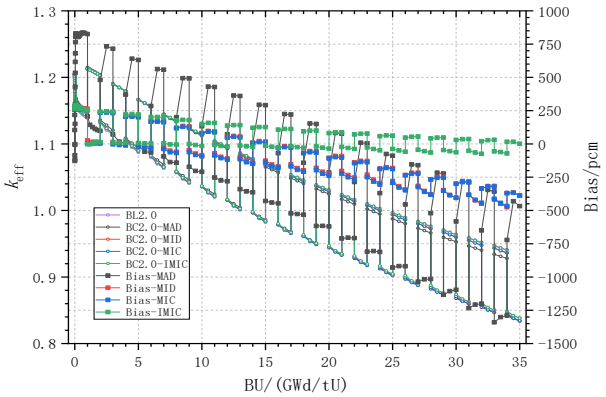
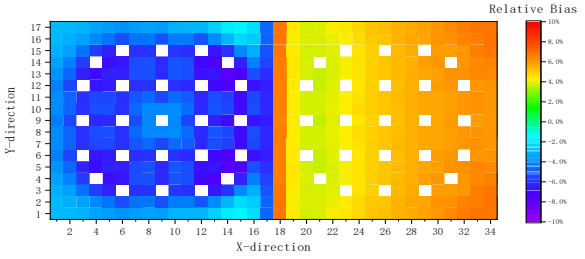
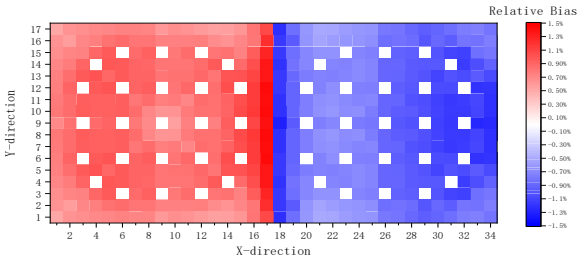


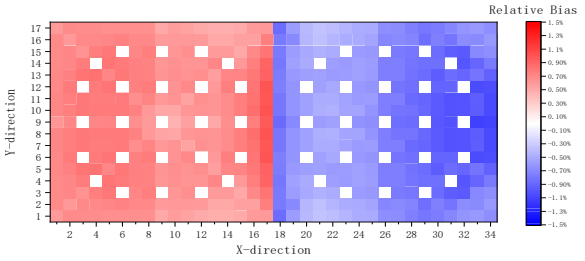
Fig. 9. Bias of k_{eff} for the MA CR movement problem



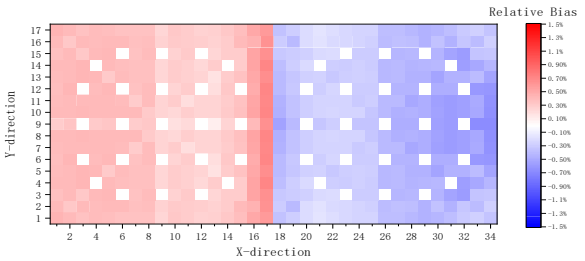
(I) MAD



(II) MID



(III) MIC



(IV) IMIC

Fig. 10. Relative bias of pin-wise power distribution for the MA CR movement problem at 35 GWd/tU

Table 1: Maximum relative bias of pin-wise power distribution for MA CR movement histories

BU GWd/tU	Methods			
	MAD	MID	MIC	IMIC
15	5.67	1.73	1.39	1.07
25	6.51	1.57	1.11	0.79
35	7.80	1.44	1.13	0.71

Table 2: RMS of the relative bias of pin-wise power distribution for MA CR movement histories

BU GWd/tU	Methods			
	MAD	MID	MIC	IMIC
15	3.79	0.55	0.37	0.30
25	4.49	0.75	0.51	0.34
35	5.29	0.89	0.72	0.39

4. Conclusions

In this summary, an improved microscopic cross-section correction method is developed in NECP-Bamboo2.0. Numerical calculations based on the single- and multi-assembly problems show that the improved microscopic XS correction method can effectively handle the CR movement history, and the bias of the k_{eff} from the reference solution obtained by this technique is kept within ±250 pcm, and the relative bias of RMS of the pin-power distribution can be within 0.05% for the single-assembly problems and 0.5% for the multi-assembly problems.

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