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High Performance Shape Annealing Matrix (HPSAM) Methodology for Core Protection Calculators

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Abstract

In CPC (Core Protection Calculator) of CE-type nuclear power plants, the core axial power distribution is calculated to evaluate the safety-related parameters. The accuracy of the CPC axial power distribution highly depends on the quality of the so called shape annealing matrix (SAM). Currently, SAM is determined by using data measured during startup test and used throughout the entire cycle. An issue concerned with SAM is that it is fairly sensitive to measurements and thus the fidelity of SAM is not guaranteed for all cycles. In this paper, a novel method to determine a high-performance SAM (HPSAM) is proposed, where both measured and simulated data are used in determining SAM.

Ⅰ. Introduction

High reliability of the core protection system in nuclear power plants should be guaranteed for safety and high performance of nuclear reactors. CPC (Core Protection Calculator)[1], a digital computer-based safety system, plays a key role of the core protection system in Ulchin Unit 3/4 (UCN Unit 3/4) which is the Korean Standard Nuclear Power Plant (KSNP), and Yonggwang Unit 3/4 (YGN Unit 3/4) which is the base model of KSNP. The four independent CPCs generate reactor trip signals based on axial power distributions synthesized using excore detector signals. Therefore, accurate axial power distribution is crucial for high reliability of CPC, which leads to high operating flexibility.

To synthesize the axial power distribution in CPC, the shape annealing matrix (SAM) should be determined via measurements, which represents a linear relationship between the excore detector signals and the peripheral core average powers. In general, accuracy of CPC power distributions highly depends on quality of SAM. A major concern about SAM is that the quality of SAM varies from cycle to cycle and the reliability of CPC tends to degrade as the core undergoes burnup.

Currently, a penalty factor is applied to the CPC claculations if the root mean square (rms) error of the CPC power distribution is larger than 8 %, compared to CECOR[2] result based on incore detector signals. It should be noted that the allowed criterion is easily reachable if SAM has poor quality. Considering the uncertainty of the CPC power distribution in the current 12～15-month cycle, it is expected that high-quality SAM should be used for longer cycle such as 18- or 24-month to guarantee the CPC reliability. Consequently, there is high demand to develop an efficient way to determine high-performance SAM. In this paper, an efficient and robust methodology to obtain a high performance SAM, HPSAM, is developed and its effectiveness is demonstrated via core follow calculations for YGN Unit 3 Cycle 2 and UCN Unit 3 Cycle 1.

Ⅱ. Shape Annealing Matrix

In reload core, the axial power distribution is obtained through a 2-step calculation in CPC. First, a least square analysis is applied to find the correlation matrix SAM between signals of the 3-segment excore detectors and 3-segment core peripheral powers, and a linear relationship (Boundary Point Power Correlation Coefficients, BPPCC) between boundary point power and the adjoining segment (top or bottom) core average power. The required data, usually 30～50 data sets, are measured during fast power ascension test(FPA) of the cycle. It takes usually 24 to 30 hours to determine SAM for a reload cycle. After SAM and BPPCC are determined, a 20-node axial power distribution is obtained via a cubic spline interpolation. Fig. 1 is a schematic diagram representing the role of SAM, where AP_i and P_i indicate core average power and peripheral core average power at segment *i*, respectively.

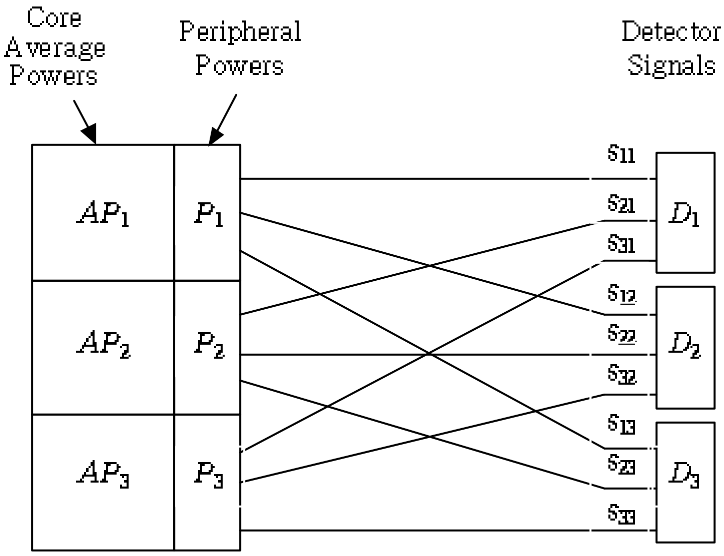


Fig. 1 Relationship between excore detector signals and core average powers

After SAM is determined, the peripheral core average power P_i can be calculated by using the following relationship.

$$\begin{pmatrix} P_1 \\ P_2 \\ P_3 \end{pmatrix} = [SAM] \begin{pmatrix} D_1 \\ D_2 \\ D_3 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{pmatrix} \begin{pmatrix} D_1 \\ D_2 \\ D_3 \end{pmatrix} \quad (1)$$

The quality of SAM dominates accuracy of the core average powers calculated by Eq. (1). Fitness of a measured SAM can be identified by checking a test value of SAM and positiveness of the inverse SAM. Test value TV_{SAM} of SAM, a matrix norm, is defined by

$$TV_{SAM} = \sum_{i=1}^{3}\sum_{j=1}^{3}|T_{ij}|,\quad T = SAM \times \begin{pmatrix} S_{11} & 0 & 0 \\ 0 & S_{22} & 0 \\ 0 & 0 & S_{33} \end{pmatrix}^{-1} \tag{2}$$

To be installed in CPC, SAM should satisfy the criterion $3 < TV_{SAM} < 6$. The lower bound denotes ideal excore detectors and the upper bound corresponds to tightly coupled excore detectors. It is involved to find exact optimal value of TV_{SAM} since it depends on many parameters related to the excore detectors. For YGN Unit 3/4 and UCN Unit 3/4, experiences have shown that the optimal test value is in the vicinity of 4.0, so TV_{SAM} should be close to 4.0 as much as possible for accurate axial power distributions. From the physical point of view, the inverse SAM represents contribution of P_i to excore detectors. Therefore, all the elements of the inverse SAM should be positive.

Ⅲ. Renormalization of the Spatial Weighting Functions

Prediction of the excore detector signals are usually done by using the spatial weighting functions, also called the shape annealing functions. For a power distribution $P(r)$, the excore detector response R can be obtained by

$$R = \int_V P(r)\omega(r)\,dr, \tag{3}$$

where $\omega(r)$ is the spatial weighting function and V denotes the core volume. The spatial weighting function for an excore detector can be efficiently calculated by solving the following adjoint transport equation

$$L^{+}\Phi^{+}(r,\Omega,E) + \Sigma_d(r,\Omega,E) = 0\ , \tag{4}$$

where L^{+} is the steady state adjoint transport operator and $\Sigma_d(r,\Omega,E)$ is detector cross section[3, 4, 5].

In this work, we use the axial spatial weighting functions which represent the spatial weighting of axial planes of the reactor core. Since the detector signal has arbitrary unit, the spatial weighting function is presented in a normalized form. For a 3-segment excore detector, the normalized axial spatial weighting function can be written as

$$\omega_{d,k} = \frac{\int_{V_k} dr_i \int\int \chi(E)\Phi_d^{+}(r_i,\Omega,E)\,d\Omega dE}{\sum_{d=1}^{3}\int_V dr_i \int\int \chi(E)\Phi_d^{+}(r_i,\Omega,E)\,d\Omega dE} \cdot \frac{V}{V_k}\ , \tag{5}$$

where $\omega_{d,k}$ is axial spatial weight of d-th detector segment and V_k is volume of the k-th core axial segment[5]. Note that $\Phi_d^{+}(r_i,\Omega,E)$ is adjoint flux subject to adjoint source at d-th detector segment.

It is well known that spatial weighting functions are insensitive to core conditions or parameters such as burnup, boron concentration, power distributions, and control rod positions, etc. This is because fast neutrons penetrating through the core vessel mainly contribute to excore detector signals. In other words, any perturbation affecting the thermal neutrons cannot be seen by the excore detectors. However, it is relatively sensitive to power level that determines the coolant temperature profile. Consequently, it can be said that the axial spatial weighting function is almost unique for a given power level.

No matter how accurately calculated the spatial weighting function is, the accuracy of estimated response of excore detectors cannot be guaranteed due to limitations of the theoretical model for the spatial weighting functions. To resolve this problem, a renormalization scheme is introduced in this work. The renormalization theory is based on the fact the spatial weighting functions for excore detectors are almost unique for a given power level, regardless of power distributions. The conventional normalized spatial weighting functions are renormalized as follows. First, it is assumed that the measured data, i.e., the axial power distribution and the corresponding detector signals at that moment, are reliable. A renormalization(or scaling) factor f_{ren} is obtained such that the renormalized spatial weighting function provides exact detector signals for the given power distribution:

$$f_{ren} = \frac{R_{measured}}{R_{calculated}} \tag{6}$$

If the renormalization factor is found using Eq. (6), the renormalized axial spatial weighting function can be obtained by

$$\omega_{ren}(z) = f_{ren}\omega(z). \tag{7}$$

The renormalized spatial weighting function has several advantages over the conventional method. First, it can minimize the inherent modelling error in calculating the weighting function and realistic characteristics of the excore detectors such as calibration, aging effect, etc. can be accounted for in the spatial weighting function. Consequently, the excore detector signal can be accurately estimated.

Fig. 2 compares conventional and renormalized axial spatial weighting functions for the 3-level excore detectors of YGN Unit 3 cycle at hot full power condition. As shown in Fig. 2, the renormalized spatial weighting functions are apparently different from those of the conventional method. The spatial weighting function is obtained with DORT[4], which is a two-dimension S_N transport code, using the BUGLE93 library[7].

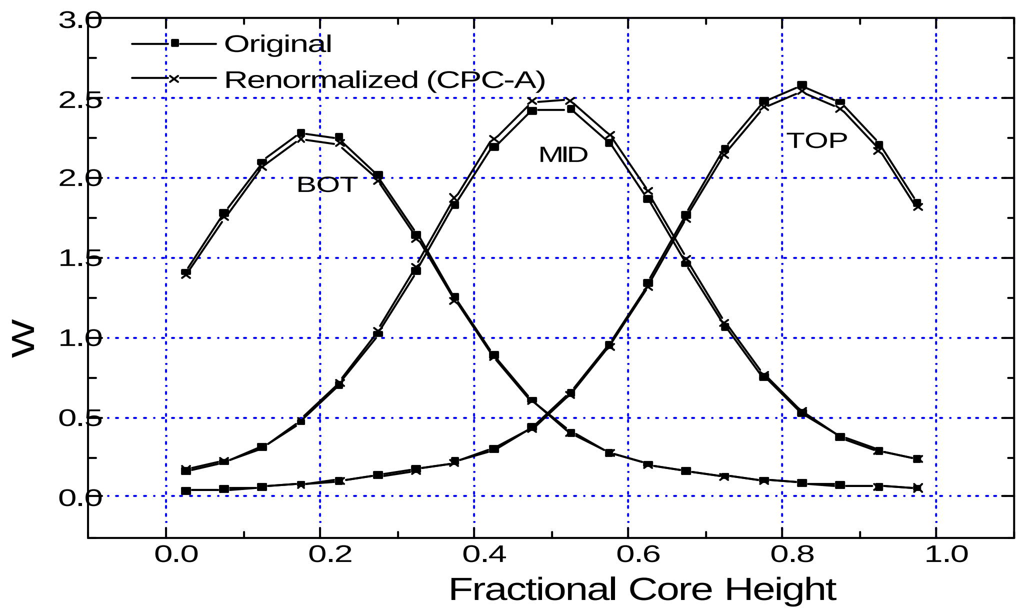


Fig. 2 Axial spatial weighting functions of excore detectors at 100% power

In Table 1, the validity of the renormalization method is demonstrated for CPC channel-A of YGN Unit 3. Table 1 shows that the accuracy of calculated detector signals is significantly improved by renormalizing the axial spatial weighting function. The renormalization factors for the three detectors are obtained for power distributions at 2,000 MWD/T and 974 MWD/T for Cycle 1 and Cycle 2, respectively, and they are used in evaluating detector responses at subsequent burnup steps. It should be noted that the renormalization factors for 5,200 and 13,650 MWD/T are similar to those of 2,000 MWD/T in YGN Unit 3 cycle 1 despite that power distributions at 5200 MWD/T and 13,650 MWD/T are quite different from that of 2,000 MWD/T. It is also observed that performance of the renormalization method is superior in Cycle 2. This is attributed to the fact that change in power distribution due to burnup in Cycle 2 is not so large as in Cycle 1. For the other 3 CPC channels, similar results are obtained. The results clearly attest to the effectiveness of the renormalization method.

Table 1. Validity of the Renormalization of the Spatial Weighting Functions

a) CPC Channel-A in YGN Unit 3 Cycle 1 at full power condition.

Burnup (MWD/T)	Detector	Measured Signal	Calculated Signal	Renormalization Factors	Renormalized Signals (Error,%)
2000	Top	0.2888	0.2934	0.98432	0.2888 (+0.00)
	Mid	0.4242	0.4148	1.02266	0.4242 (+0.00)
	Bot	0.2870	0.2917	0.98389	0.2870 (+0.00)
5200	Top	0.3032	0.3111	0.97461	0.3064 (+1.05)
	Mid	0.4054	0.3944	1.02789	0.4036 (-0.44)
	Bot	0.2914	0.2945	0.98947	0.2900 (-0.48)
13650	Top	0.3225	0.3305	0.97579	0.3259 (+1.05)
	Mid	0.3796	0.3687	1.02956	0.3777 (-0.50)
	Bot	0.2979	0.3008	0.99036	0.2964 (-0.50)

b) CPC Channel-A in YGN Unit 3 Cycle 2 at full power condition.

Burnup (MWD/T)	Detector	Measured Signal	Calculated Signal	Renormalization Factors	Renormalized Signals (Error,%)
974	Top	0.3399	0.3352	1.01402	0.3399 (+0.00)
	Mid	0.3865	0.3807	1.01524	0.3865 (+0.00)
	Bot	0.2736	0.2841	0.96304	0.2736 (+0.00)
5242	Top	0.3325	0.3271	1.01651	0.3319 (-0.18)
	Mid	0.3846	0.3782	1.01692	0.3842 (-0.13)
	Bot	0.2829	0.2947	0.95996	0.2840 (+0.39)
10108	Top	0.3371	0.3330	1.01231	0.3378 (+0.21)
	Mid	0.3786	0.3709	1.02076	0.3768 (-0.47)
	Bot	0.2842	0.2961	0.95981	0.2853 (+0.39)

Ⅳ. High Performance Shape Annealing Matrix (HPSAM)

Ⅳ.1 Methodology

Accuracy of the axial power distributions synthesized in CPC depends on two addressable constants SAM and BPPCC. Among them, SAM dominates the accuracy since the 3-segment core average powers are directly determined by SAM. Thus, it is essential to ensure high-quality SAM to get accurate CPC power distribution. It is worthwhile to note that the elements of SAM are quite sensitive to measured data and thus vary from cycle to cycle. However, BPPCCs are fairly insensitive to measured data.

The purpose of this work is to develop an efficient and robust method to determine a high performance SAM (HPSAM) for the reload core. Drawback of current method to determine SAM, as identified in Section 2, is that the quality of SAM highly depends on measured data, i.e., incore and excore detector signals. Unfortunately, many of the measured data are of poor quality due to instrument failure, poorly or uncalibrated instrumentation, and high noise levels, etc. Therefore, it cannot be guaranteed that SAM of high quality is always obtained.

The essence of the new methodology to determine SAM is to combine simulated data using the axial spatial weighting functions for excore detectors. As discussed in Section Ⅲ, accurate response of an excore detector at a power level can be predicted with the aid of the renormalization method if a reliable measured data is available. Once the renormalization factors are determined, a number of noise-free data set for excore detector signals can be obtained via computer simulation and used in finding the HPSAM. Major advantages of the new method is that fairly accurate data, which cannot be measured at the stage of reactor startup, can be used in determining SAM. Furthermore, the HPSAM can be found quickly right after measuring the reference data since the spatial weighting functions can be calculated in advance.

Once the renormalization factors are determined for each CPC channel, an envelope of power distributions are required to find the HPSAM. In this work, two kinds of axial power distributions are utilized for all channels. One is from a Xenon oscillation simulation performed for YGN Units 3 Cycle 2, the other is the typical saddle type power shapes obtained with the full power depletion calculations of the Korean Next Generation Reactor (KNGR) core.

Ⅳ.2 Application to YGN Unit 3 Cycle 2 and UCN 3 Cycle 1

In cycle 2 of YGN Unit 3, 49 data sets were measured during the fast power ascension test to determine SAM and BPPCC for each CPC channel. SAMs used in cycle 2 are shown in the left side of Table 2 a). Considering the inverse SAM matrices and test values of SAMs, it can be said that CPC-A, C, D have relatively good SAM while CPC-B has poor SAM. Poor quality of SAM for CPC-B can be explained by the fact that the inverse SAM has two negative elements and the test value is far from the optimal value 4.0. Comparing four SAMs, it is observed that CPC-C has the best one.

HPSAMs for YGN Unit 3 Cycle 2, recalculated by using the renormalization method, are shown in the right side of Table 2 a). The renormalization factors for the 4 channels were determined using a reference data taken at 80% power level. As shown in the right side of Table 2 a), it is clear that all HPSAMs have good test values and all elements of inverse matrices are positive values. Especially, it should be noted that the quality of SAM for CPC-B is significantly improved.

In cycle 1 of UCN Unit 3, 166 data sets are measured during the Xenon oscillation experiment to determine SAM and BPPCC for each channel, SAMs used in cycle 1 are shown in the left side of Table 2 b). Considering the inverse SAM matrices and test values of SAMs, it can be said that all CPC channel have relatively good SAM.

For UCN Unit 3 Cycle 1, the renormalization factors are evaluated using a reference data taken at 80% power level. HPSAMs for UCN Unit 3 Cycle 1 are shown in the right side of Table 2 b). It is clear that all HPSAMs have good test values and all elements of inverse matrices are positive values.

Table 2. Properties of the Installed SAM and HPSAM

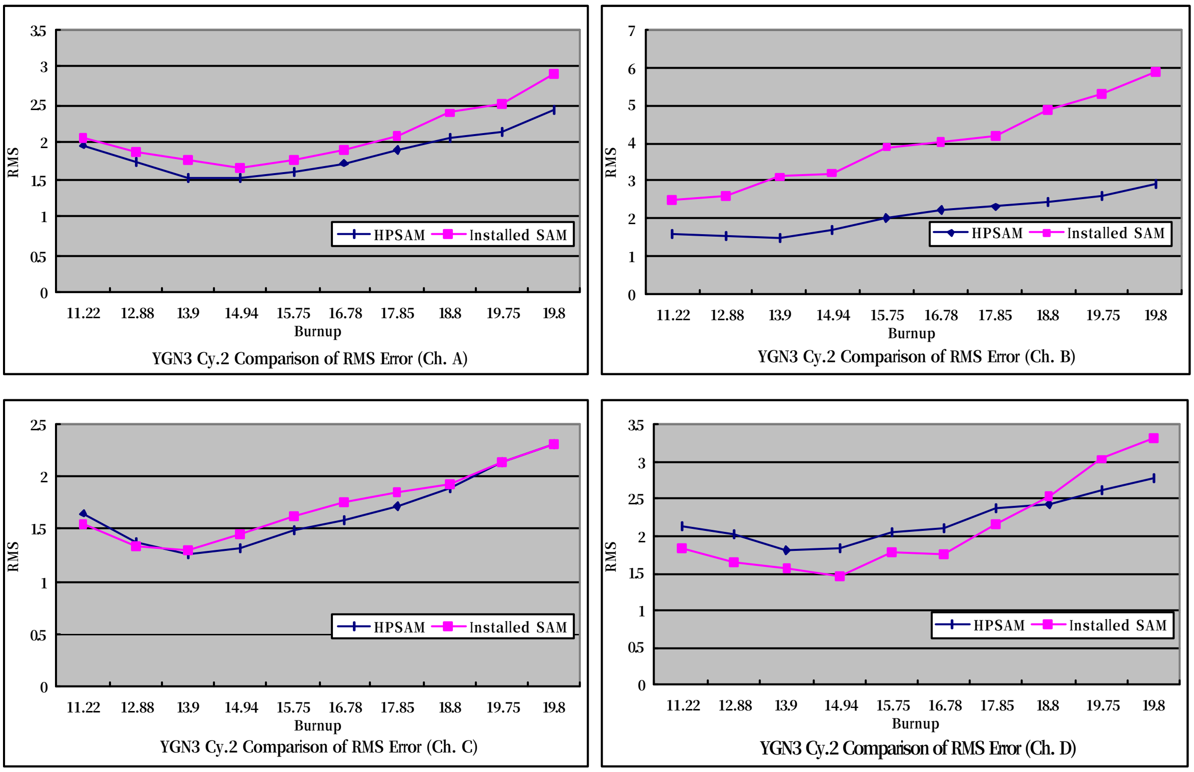
a) for YGN Unit 3 Cycle 2

Installed ASM				HPSAM		
Channel	SAM	Inverse SAM	Test Value	SAM	Inverse SAM	Test Value
CPC-A	4.5397 -0.2905 -1.5600, -0.7580 3.6646 -0.2673, -0.7817 -0.3740 4.8272	0.2383 0.0269 0.0785 0.0524 0.2803 0.0325 0.0426 0.0261 0.2224	3.8990	3.8295 -0.7006 -0.1739 -0.9828 4.6549 -1.3577 0.1533 -0.9542 4.5316	0.2719 0.0459 0.0242 0.0583 0.2387 0.0738 0.0031 0.0487 0.2354	3.9902
CPC-B	5.2913 -2.3617 0.6197, -0.3447 3.6017 -0.8293, -1.9466 1.7600 3.2096	0.1960 0.1305 -0.0041 0.0410 0.2738 0.0628 0.0964 -0.0710 0.2746	5.0289	3.8775 -0.6637 -0.1884 -1.0167 4.5752 -1.3866 0.1392 -0.9115 4.5750	0.2685 0.0438 0.0243 0.0609 0.2425 0.0760 0.0040 0.0470 0.2330	3.9867
CPC-C	4.3385 -0.4846 -0.9101, -0.8709 4.1603 -0.9288, -0.4677 -0.6757 4.8389	0.2436 0.0370 0.0529 0.0581 0.2569 0.0602 0.0317 0.0394 0.2202	3.9674	3.8945 -0.6798 -0.1650 -1.0300 4.6084 -1.3368 0.1354 -0.9286 4.5017	0.2676 0.0441 0.0229 0.0611 0.2409 0.0738 0.0046 0.0484 0.2367	3.9819
CPC-D	4.6510 -0.9608 -0.6811, -0.3466 3.3753 -0.4288, -1.3044 0.5855 4.1098	0.2318 0.0583 0.0445 0.0326 0.2992 0.0366 0.0689 -0.0241 0.2522	4.0832	3.8919 -0.6799 -0.1661 -1.0280 4.6087 -1.3391 0.1361 -0.9288 4.5052	0.2678 0.0441 0.0230 0.0610 0.2409 0.0739 0.0045 0.0483 0.2365	3.9823

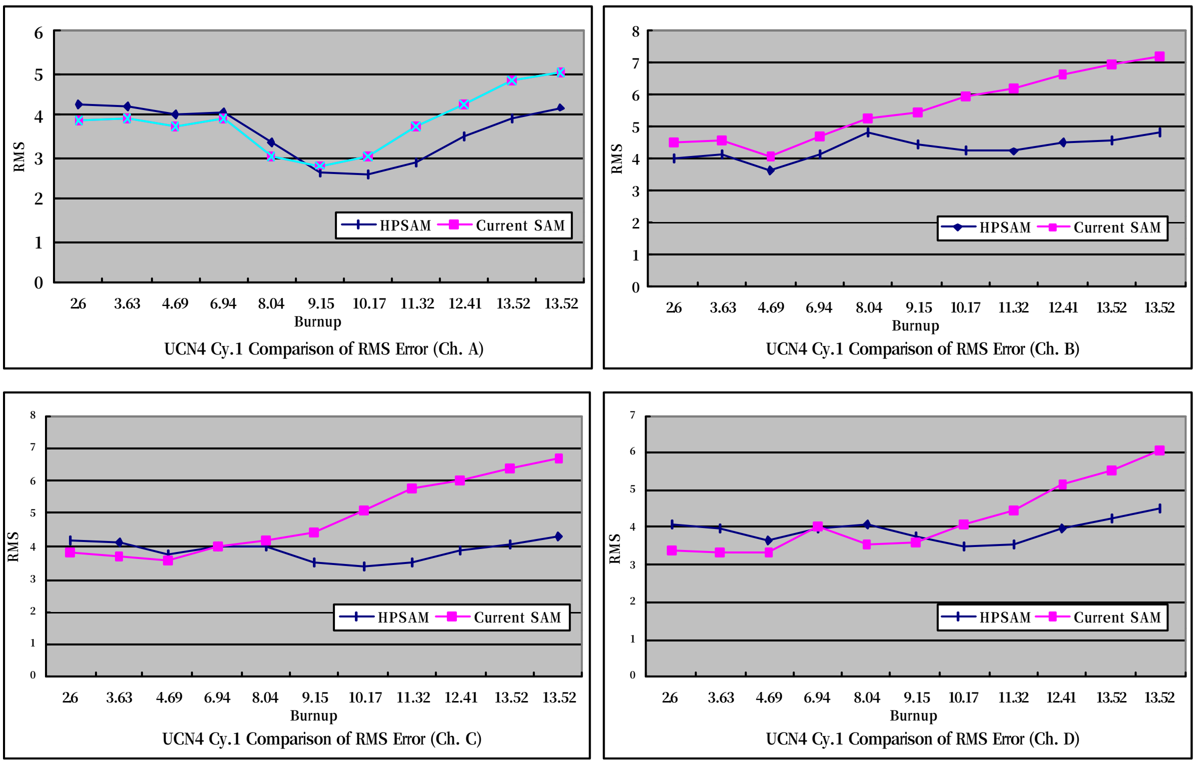
b) for UCN Unit 3 Cycle 1

Installed ASM				HPSAM		
Channel	SAM	Inverse SAM	Test Value	SAM	Inverse SAM	Test Value
CPC-A	4.3325 -0.9494 -0.0927 -1.1644 4.7733 -1.4256 -0.1681 -0.8238 4.5183	0.2458 0.0526 0.0216 0.0663 0.2358 0.0757 0.0212 0.0449 0.2359	4.0151	3.9527 -0.6826 -0.1396 -1.0685 4.5989 -1.2928 0.1159 -0.9163 4.4324	0.2641 0.0434 0.0210 0.0631 0.2412 0.0723 0.0061 0.0487 0.2400	3.9705
CPC-B	4.7728 -1.2681 -0.0727 -1.4140 4.8585 -1.2996 -0.3588 -0.5904 4.3723	0.2298 0.0627 0.0225 0.0746 0.2339 0.0708 0.0289 0.0367 0.2401	4.0678	3.9368 -0.6858 -0.1431 -1.0569 4.6061 -1.3005 0.1202 -0.9204 4.4436	0.2651 0.0437 0.0213 0.0625 0.2409 0.0725 0.0058 0.0487 0.2395	3.9726
CPC-C	4.6973 -1.3130 0.0797 -1.4523 4.9983 -1.4681 -0.2450 -0.6853 4.3883	0.2335 0.0637 0.0171 0.0751 0.2302 0.0756 0.0248 0.0395 0.2406	4.1138	3.9655 -0.6835 -0.1338 -1.0780 4.6002 -1.2802 0.1126 -0.9168 4.4140	0.2633 0.0432 0.0205 0.0635 0.2411 0.0719 0.0065 0.0490 0.2410	3.9684
CPC-D	4.5429 -1.0675 -0.1410 -1.4376 5.0328 -1.5294 -0.1053 -0.9653 4.6704	0.2382 0.0554 0.0253 0.0744 0.2293 0.0773 0.0207 0.0486 0.2307	4.1012	3.9608 -0.6798 -0.1390 -1.0745 4.5929 -1.2911 0.1136 -0.9130 4.4301	0.2636 0.0432 0.0209 0.0634 0.2415 0.0724 0.0063 0.0487 0.2401	3.9696

By using the HPSAMs, the core follow calculations are performed to demonstrate the improved performance of the newly determined SAMs. In Fig. 3 a), the accuracy of the CPC power distribution for the YGN 3 Cycle 2 is compared with the results of CECOR. It is observed that 4 CPCs with HPSAM have smaller rms error than the original CPCs. It should be noted that CPC-B shows much smaller rms error with HPSAM, compared with the large uncertainty with the original SAM. CPC-A, C, and D show slight improvement since the original SAMs are good enough. In Fig. 3 b), the accuracy of the CPC power distribution for the UCN 3 Cycle 1 is compared with the results of CECOR. It is observed that 4 CPCs with HPSAM have smaller rms error than the original CPCs.



a) for YGN Unit 3 Cycle 2



b) for UCN 3 Cycle 1

Fig. 3-2 Core follow results with installed SAM and HPSAM

V. Conclusions

In this paper, for accurate estimation of excore detector responses, a renormalization method is introduced. By renormalizing the spatial weighting function to the measured data, accurate detector signals can be obtained for a given axial power distribution. Based on the renormalization scheme, a novel method to determine the high performance SAM (HPSAM) for CPC is proposed and its effectiveness is validated. Unlike the current method, simulated data are used in the HPSAM methodology.

Application of the new method to YGN Unit 3 cycle 2 and UCN Unit 3 cycle 1 shows that the new method can provide SAM of high fidelity. Prediction error of CPC power distributions with respect to the CECOR results remains fairly small throughout the entire core cycle. We conclude that HPSAM can be efficiently obtained in both initial and reload cycles and it can be used with high reliability throughout the cycle even in 18-month cycle operation. Consequently, the new method will result in improved operational flexibility.

We have shown that the reliability of CPC can be significantly improved by using the new method developed in the present work. In CE-type nuclear power plant, the thermal margin is directly affected by the uncertainty of CPC. Therefore, it is potentially expected that additional thermal margin can be available by applying the HPSAM methodology.

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