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On-line Generation of Three-Dimensional Core Power Distribution Using Incore Detector Signals to Monitor Safety Limits

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Abstract

It is essential in commercial reactors that the safety limits imposed on the fuel pellets and fuel clad barriers, such as the linear power density (LPD) and the departure from nucleate boiling ratio (DNBR), are not violated during reactor operations. In order to accurately monitor the safety limits of current reactor states, a detailed three-dimensional (3D) core power distribution should be estimated from the in-core detector signals. In this paper, we propose a calculation methodology for detailed 3D core power distribution, using in-core detector signals and core monitoring constants such as the 3D Coupling Coefficients (3DCC), node power fraction, and pin-to-node factors. Also, the calculation method for several core safety parameters is introduced. The core monitoring constants for the real core state are promptly provided by the core design code and on-line MASTER (Multi-purpose Analyzer for Static and Transient Effects of Reactors), coupled with the core monitoring program. Through the plant computer, core state variables, which include reactor thermal power, control rod bank position, boron concentration, inlet moderator temperature, and flow rate, are supplied as input data for MASTER. MASTER performs the core calculation based on the neutron balance equation and generates several core monitoring constants corresponding to the real core state in addition to the expected core power distribution. The accuracy of the developed method is verified through a comparison with the current CECOR method. Because in all the verification calculation cases the proposed method shows a more conservative value than the best estimated value and a less conservative one than the current CECOR and COLSS methods, it is also confirmed that this method secures a greater operating margin through the simulation of the YGN-3 Cycle-1 core from the viewpoint of the power peaking factor for the LPD and the pseudo hot pin axial power distribution for the DNBR calculation.

Key Words : core power distribution, monitoring constants, in-core detector signals, 3DCC, safety limits, ECOMS

1. Introduction

Detailed three-dimensional (3D) core power distribution monitoring in operating power reactors is a prerequisite for ensuring that various safety limits imposed on fuel pellets and fuel clad barriers, such as the linear power density (LPD) and the departure from nucleate boiling ratio (DNBR), are not violated during reactor operations. Most commercial power reactors have some type of fixed or movable in-core detectors and ex-core detectors. Also, these facilities are equipped with an on-line or off-line core power or flux distribution monitoring program to estimate the 3D power distribution by a combined use of detector signals and pre-calculated monitoring constants. For example, the YGN-3 pressurized water reactor (PWR) [1], the first ABB Combustion Engineering (ABB-CE) PWR in Korea, has self-powered rhodium fixed in-core neutron detectors installed at 45 fuel assembly (FA) sites on five axial levels. The CECOR code [2] and Core Operating Limit Supervisory System (COLSS) [3] of the CE PWR convert the rhodium detector signals to detector box powers using pre-determined constants, and then determine the uninstrumented FA powers using pre-calculated coupling coefficients (CC), which are defined as the inverse ratio of the power of a given FA to the average power of the four surrounding FA's at each detector level. The detailed FA axial power distribution is also determined by fitting the five detector box powers along each FA by a five-mode Fourier series. The Wolsung unit 1, the first CANadian Deuterium Uranium (CANDU) reactor in Korea [4], has two types of in-core detectors in the core: platinum detectors and vanadium detectors. The platinum detector, which is called a platinum-clad inconel detector, is an inconel core surface coated with a platinum emitter. The 130 in-core flux detectors of the regulating system (which contains 102 vanadium and 28 platinum detectors) are installed in separate detector wells in 26 vertical detector assemblies appropriately located in the core. Platinum detectors have a mixed response, being sensitive to both neutrons and gamma rays, and approximately 90 % of the detector signal is prompt. Vanadium detectors are neutron sensitive only, and have a relatively slow response to flux changes. Because of their prompt response time, platinum detectors are used in the regulating system and in the two shutdown systems, while vanadium detectors are used in the regulating system for flux mapping only. The CANDU on-line flux mapping system [5] converts the 102 vanadium detector signals to thermal fluxes at the detector sites and then maps out the 3D flux distribution by a process of least-squares fitting of the measured thermal fluxes to a linear expansion of pre-calculated flux modes. These methods, which use the pre-calculated coupling coefficients, weighting constants or flux modes, run fast but they are inaccurate, especially for asymmetrical axial power distribution, because they are unable to take into account the core operation history and transient situation caused by an operator action such as control rod insertion/withdrawal and boration/dilution or xenon transient.

For improved core power monitoring, studies to improve the prediction accuracy of the current methods have been undertaken [6-9], and new methods that directly use core neutronics design equations have been proposed [10-13].

In this paper, the methodology of generating 3D power information for core monitoring by using detector signals and several core monitoring constants, such as the 3D Coupling Coefficients (3DCC) and the pin-to-node factors, is studied and the core monitoring program ECOMS is developed. The 3DCC and several core monitoring constants for peak power calculation are provided promptly by the core design code, MASTER (Multi-purpose Analyzer for Static and Transient Effects of Reactors) [14], which is on-line and is coupled with the core monitoring program.

MASTER is a nuclear analysis and design code that can simulate the pressurized water reactor core or the boiling water reactor core in 1-, 2-, or 3-dimensional Cartesian or hexagonal geometry. MASTER analyzes the steady-state and transient core behaviors. The major calculation modules for the design application consist of depletion, steady-state flux, transient flux, pin power, pin burnup, xenon dynamics, adjoint flux, thermal hydraulics, and design-specific activities like fuel management. MASTER performs microscopic depletion calculations using microscopic cross sections and also has the pin information reconstruction capability. Its neutronics model solves the space-time dependent neutron diffusion equations with modern nodal methods. It is a multi-purpose and multi-function integrated code that is designed to provide fuel pin information and detailed T/H conditions.

Through the plant computer, core state variables such as reactor thermal power, control rod bank position, boron concentration, inlet moderator temperature, and flow rate, are supplied as input data for MASTER. MASTER performs the core calculation based on the neutron balance equation by using the modern nodal method and generates several core monitoring constants corresponding to the real core state. After the core monitoring constants are supplied promptly, the 3D power distribution and the several peaking factors are calculated using the in-core detector signals. Based on the detailed 3D power distribution data, ECOMS also calculates the power peaking factor (F_q) for the LPD, the pseudo hot pin axial power distribution for the DNBR calculation, the quadrant power tilt, the axial power deviation, and so forth. The developed method is verified through a simulation of the YGN-3 Cycle-1 core from the viewpoint of 3D power distribution, the F_q, and the pseudo hot pin axial power distribution.

2. Computing Method for Core 3D Power Distribution

2.1. Conversion of a Detector Signal to a Box Power

The in-core detectors of the YGN-3 use self-powered rhodium neutron detectors. These rhodium neutron detectors use the beta decay of the daughter nucleus ^{104}Rh that is produced in the (n, γ) reaction of ^{103}Rh. ^{103}Rh absorbs an epithermal neutron and is converted to ^{104}Rh or ^{104m}Rh and is then decayed by emitting beta-electrons. The beta decay scheme of rhodium involves two radioisotopes. The predominant (92.3 %) mode is the beta decay of ^{104}Rh with a 42 second half-life, while the other mode (7.7 %) is the two stage decay from ^{104m}Rh by both beta and gamma emissions with a 4.4 minute half-life, followed by beta decay of ^{104}Rh. The emitted electrons are collected in the inconel-sheath of the detector and generate a current signal. The rhodium detector is located in the center of a FA and produces a current signal that is proportional to the neutron reaction rate. The current signal is compensated for by a background detector signal and by considering the delay effect by the half-lives of ^{104}Rh and ^{104m}Rh, and then a compensated detector current signal is recorded. This current signal of a detector is converted into the power of a detector box by using the signal-to-power conversion factor [2].

2.2. Calculation of Box Power Distribution with the 3DCC

In-core detector signals are converted into detector box power through signal processing. The 3D power distribution for the core monitoring seeks the powers of the uninstrumented fuel assemblies using the measured box powers of the instrumented fuel assemblies. This calculation is performed simultaneously for the whole core using the 3DCC. The 3DCC is defined as the ratio of the average power of the surrounding boxes by adjoining three dimensions to the power of the box ik as follows:

$$< 3DCC >_{i,k} = \frac{1}{N_i P_{i,k}} \sum_{j=1}^{N_i} P_{j,k}^{i} . \tag{1}$$

where j represents the index of the FA abut on the FA i, and N_i represents the total number of the abuting j assemblies. For the FA box located at the central core, N_i is 6 including the top, bottom, east, west, north, and south boxes but, for the FA box at the core edge, contacting with the reflector N_i can be 3 or 4 or 5. The 3DCC is generated by the MASTER code or a core design code. Because the calculated 3DCC' s are provided beforehand, the power of the uninstrumented fuel assemblies can be solved by Eq. (2).

$$N_{i,k} < 3DCC >_{i,k} P_{i,k} - \sum_{j \in U} P_{j,k}^{i} = \sum_{l \in I} P_{l,k}^{i} . \tag{2}$$

where U represents the group of uninstrumented fuel assemblies and I is the opposite instrumented group. Eq. (2) is applied to all the boxes and can be expressed as the following matrix-vector form:

$$Ap = s . \tag{3}$$

If we solve Eq. (3), we can obtain all the box powers throughout the whole core.

2.3. Calculation of Detailed 3D Power Distribution

Even if a FA can be divided into several nodes in the radial direction for the accurate neutron balance calculation of MASTER, ECOMS still treats one FA as a detector box in the radial direction and as 1 - 4 nodes, according to the in-core detector size in the axial direction. Therefore, if the power distribution in a detector box is supposed to have the same axial power distribution as the calculation result of MASTER or of a design code, we can easily calculate the detailed 3D power distribution of all the fuel assemblies using the node power fraction $<PF>_{ikz}$. $<PF>_{ikz}$ is defined as the power fraction of a node z belonging to the box ik to the total power of box ik as follows:

$$< PF >_{ikz} = \frac{p_{ik}^{z,M}}{P_{ik}^{M}} . \tag{4}$$

where superscript M means that this value comes from the MASTER calculation. Using Eq. (4), the power of each node can be calculated directly as follows:

$$p_{ik}^{z} = < PF >_{ikz} \times P_{ik} . \tag{5}$$

where p_{ik}^{z} is defined by the power of the axial node z belonging to the detector box ik.

The total thermal power of the core is achieved by combining all the calculated 3D powers. However, this value is not used because it can be different from the core power calculated by the heat balance method of the secondary side, which is a reference value. Therefore, the calculated core 3D power distribution is normalized and we will treat the relative 3D power distribution.

3. Computing Method for Monitoring Parameters

ECOMS calculates the Limiting Conditions for Operation (LCOs) including the LPD, DNBR, power of the whole core, the quadrant power tilt, the axial power deviation, and so forth. It compares the calculated values and the limiting ones, and provides alarms so that a plant operator can effectively monitor the operating states of the core and can maintain the core states within a range of limited operating conditions. LCOs are monitored based on the detailed 3D power distribution data using the in-core detector signals, and other values such as the 3D power peaking factor (F_q), plane power peaking factor (F_{xy}), and axial power peaking factor (F_z) are also monitored.

3.1. Calculation of Peak Power Values

Knowledge of detailed pin information is essential for accurate calculations of the core peaking factor and for the minimum DNBR evaluation. The MASTER code calculates the local heterogeneous fuel pin power distributions in each axial segment within a FA. The calculation is performed by modulation of the local homogeneous distributions based on the pin power reconstruction method and heterogeneous power form functions describing the fine structure of the assembly. The form functions are prepared from a lattice code while an effective cross section is generated.

Based on the MASTER result of the local pin power reconstruction, the peak pin power in each FA is calculated using a pin-to-node factor $<PF>_{ikz}$ in the proposed method.

$$HP_{ik}^{z} = <PN>_{ikz} \times p_{ik}^{z}, \tag{6}$$

where HP_{ik}^{z} is the maximum fuel pin power of the node z in the box ik, and p_{ik}^{z}, the power of the axial node z belonging to the detector box ik, is determined by using the power fraction $<PF>_{ikz}$. The pin-to-node factor is defined by the ratio of the maximum fuel pin power to the average fuel pin power in a box and is provided by a calculation of the MASTER code at each calculation time step of ECOMS.

$$<PN>_{ikz} = \frac{HP_{ik}^{z,M}}{p_{ik}^{z,M}}, \tag{7}$$

where $HP_{ik}^{z,M}$ and $p_{ik}^{z,M}$ represent the maximum fuel pin power and the average fuel pin power in a box, respectively, as calculated by the MASTER code.

If the 3D power distribution ($p_{ik}^{z,M}$) for all the FA nodes in a core and the maximum fuel pin powers of all the nodes are calculated, the assemblywise power peaking factor (F_{qi}) and the power peaking factor of the whole core (F_q) can be determined. Also, $F_{xy}(z)$, as a function of the axial position and the maximum F_{xy}, can be calculated from the normalized power distribution in a plane perpendicular to the z axis. The radial power peaking factor of a FA (Fr_i) and the radial power peaking factor of a core (Fr) are calculated from the power distribution integrated over the axial direction. To calculate Fr_i and Fr, information about the fuel pin power that is integrated over the axial direction is needed. Defining the Fr-pin-to-node factor ($<FrPN>_i$) in a similar way as $<PN>_{ikz}$

in the proposed method, the radial power peaking factor (*Fr*) is solved from a 2D power distribution integrated axially.

$$< FrPN >_i = Fr_i^M / P_i^M \quad (8)$$

Fr_i^M and P_i^M represent the maximum fuel pin power and average fuel pin power of the boxes in the radial direction that are obtained by integrating 3D power distribution over the axial direction and by normalizing it. Therefore, *Fr* is calculated by the following Eq. (9), and Fr_i is the maximum value of all the Fr_i values.

$$Fr_i =< FrPN >_i \times P_i \quad (9)$$

The core average axial power distribution $P1D(z)$ is calculated from the core 3D power distribution, and the maximum axial power F_z is determined from this axial power distribution. The F_q calculated in the proposed method is a best-estimated value calculated from the detailed 3D power distribution data. The core power margin by LPD can be calculated by F_q.

3.2. Calculation of Pseudo Hot Pin Power Distribution

In order to calculate the operating margin by DNBR, the axial power distribution of a pseudo hot pin, $HP1D(z)$, is determined by multiplying the planewise peaking factor $F_{xy}(z)$ and the average axial power distribution $P1D(z)$ for each plane:

$$HP1D(z) = P1D(z) \times Fxy(z) . \quad (10)$$

This approach always provides a more conservative DNBR value than that of the hot pin power where the real minimum DNBR occurs. Also, this calculation method secures a larger operating margin than the COLSS and CECOR methods ($P1D(z) \times Max\{F_{xy}(z)$ *according to the CR configurations*}) used in the existing CE-type commercial reactors.

4. Verification Calculation

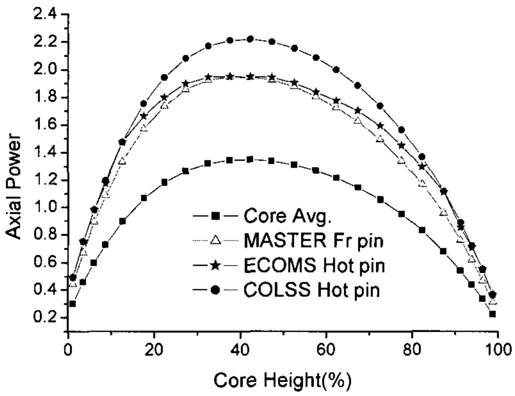
The method introduced in this paper was examined by purely numerical experiments for core power distribution calculations in the YGN-3 Cycle-1, the first ABB-CE PWR in Korea with fixed in-core rhodium detectors installed at the 45 FA locations on five axial levels. For the numerical experiment, reference 3D power distributions in the YGN-3 Cycle 1 core are calculated by the MASTER code and are presumed to be the true 3D power distributions. Then, the simulated detector box signals are constructed using the 3D nodal powers at the instrumented nodes from the reference 3D power distribution. Finally, a comparison of the monitored 3D power distribution and the reference is made to establish the prediction accuracy of the proposed method.
To validate the proposed method, one may use the detector measurements instead of the simulated detector box signals. However, considering that not only the true power distribution but also the exact core states, such as the isotopic composition and thermal-hydraulic conditions at the time of monitoring, are always unknown, it is exceptionally difficult to isolate the prediction errors of the proposed method and, therefore, it is hard to make a fair evaluation of the validity of the method. For this reason, pure numerical experiments were examined to validate the proposed method.

To verify the proposed method, the core 3D power distribution, the core power peaking factor, and the pseudo hot pin axial power distribution for four different core states was conducted. Results were compared with those of MASTER and of ECOMS by using the simulated detector signals. The four cases are: the YGN-3 Cycle-1 all rod out

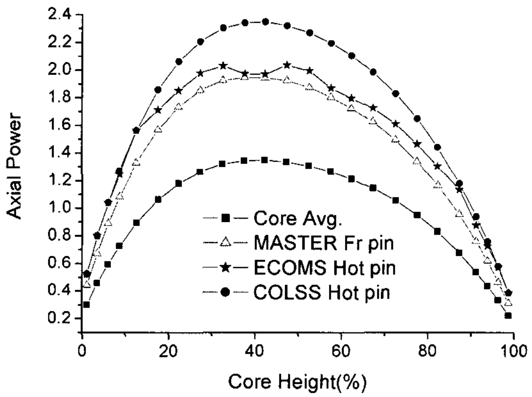
(ARO) cores at the beginning of the cycle (BOC) at 100 % power; the middle of the cycle (MOC) at 100 % power; the end of the cycle (EOC) at 100 % power; and a case in which control rods were inserted at EOC at 70 % power with axially skewed power distribution. As such, we calculated 3D power distribution using the 4 nodes-per-fuel assembly (N/A) nonlinear Analytical Nodal Method (ANM) and assumed it to be the true 3D power distribution. We used the nodal powers at the instrumented nodes to simulate the 225 detector box powers from the 4 N/A reference calculations. The reactor core of YGN-3 is 381.0 cm in axial length. Each FA is divided into 26 axial nodes: two reflector nodes, 12 instrumented nodes, and 12 uninstrumented nodes. For the 12 instrumented axial nodes, each of the 40-cm-long rhodium detectors located near the top and the bottom of the core are divided into three axial nodes (10, 10, 20 cm), while the other three inner detectors are all divided into two equal-length nodes, each measuring 20 cm.

Table 1 shows a comparison of the core 3D power distribution between the reference values of MASTER and the results of the proposed method. The calculation results of the current CECOR method are also displayed in Table 1 for an easy comparison of the accuracy of these methods. The value of the data in parentheses in Table 1 expresses the difference with the MASTER result. A consistent case without signal errors and a case with signal errors are compared for one core state. For all the consistent cases without signal errors, the 3D node power distribution errors are 0 % in the proposed method but the errors in the CECOR method are higher than 2%. These errors for the consistent cases come from the Fourier expansion of axial power distribution. The CECOR method calculates the FA axial power distribution by interpolating the five-level detector box powers along the FA by a five-mode Fourier series expansion. Because of the inaccuracy of boundary conditions at the top and bottom of the core and of the interpolation itself, the axial power distribution cannot be reproduced exactly using the CECOR method, even for a consistent case. On the other hand, the calculation results of the proposed method reproduce the reference MASTER power distribution. This result demonstrates the robustness of the proposed method. Therefore, if there are no uncertainties in the numerical solution method and in the detector signals, the core power distribution monitoring error in ECOMS depends on the calculation error of the MASTER code power distribution; in other words, the accuracy of the theoretical model of the MASTER represents the real core. The theoretical model, however, will not be perfect in the real core because there are always uncertainties in the control rod position measurement, the coolant densities, the fuel temperature, the cross sections, the lattice properties, and the fuel burnup distribution used in the MASTER calculation. However, for the purposes of the numerical experiment, we supposed that they were perfect and all uncertainties were included in detector signal errors.

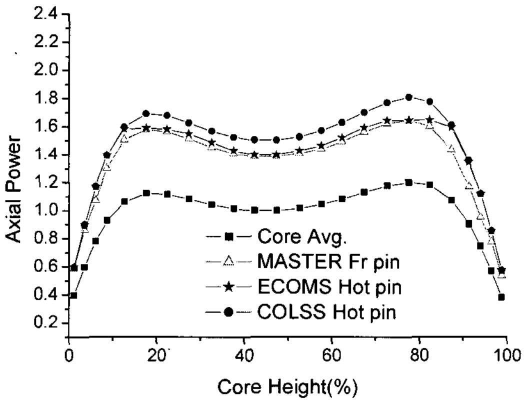
In order to investigate the effect of the detector reading errors, the normal distribution signal errors, with a zero mean and 10 % three sigma (3σ=10%, RMS≈3%), are randomly applied to the simulated detector signals and are compared to the 3D power distribution based on the proposed method. Because it is known that the uncertainty of the in-core detector readings is about 3.3 %, the normally distributed 1σ error has a zero mean. The normal distribution signal errors are generated through the rejection technique by random sampling. Each signal error is multiplied to the simulated detector signal and the signal value is changed as much as the amount of the error. Although the random normal distribution



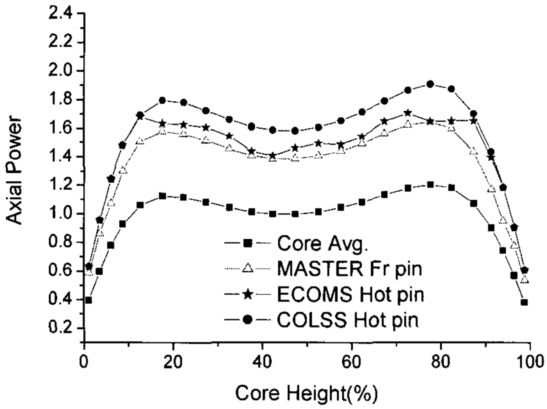
(a) BOC 100% power without signal errors



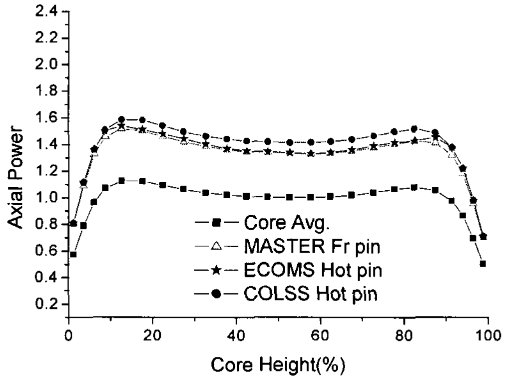
(b) BOC 100% power with signal errors



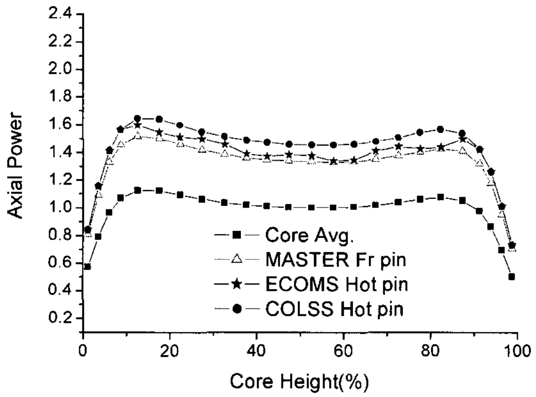
(c) MOC 100% power without signal errors



(d) MOC 100% power with signal errors



(e) EOC 100% power without signal errors



(f) EOC 100% power with signal errors

Fig. 1. Comparison of the Axial Power Distribution for a Pseudo Hot Pin

signal errors with a zero mean and 10 % three sigma are applied, the 3D power distribution of ECOMS is reproduced within the maximum 1.6 % RMS error. The CECOR method, however, shows a maximum error of 5.1 %. Also, ECOMS estimates peak values more accurately than the CECOR method for all cases.

Table 2 shows the F_q values for monitoring the operational limits of the linear power density calculated by the COLSS, CECOR, and ECOMS methods. Assuming no signal errors, the F_q values calculated by the proposed method are equal to the values calculated by MASTER. The values represented by COLSS and CECOR in Table 2 are calculated by the COLSS method, which multiplies the maximum F_z of the axial average core power by the core maximum value F_{xy}, except for the top and bottom 10 % regions of core height. The core average axial power distribution in COLSS is computed by a five-mode Fourier series expansion with each level averaged detector signals, while the CECOR core average axial power distribution comes from the 3D FA power distribution interpolated by the CECOR

Table 1. Comparison of the Core 3D Power Distribution

BU	Power	Signal Error	Method	3D Node Power	Peak Power Value(Difference[a])		
	CR			RMS Error(%)	Fr	Fz	Max{Fxy(z)}
BOC	100% ARO[b]	No	ECOMS	0.00	1.442(0.000)	1.348(0.000)	1.647(0.000)
			CECOR	2.05	1.441(-0.001)	1.345(-0.003)	1.648(0.001)
		Max 10%[c]	ECOMS	1.44	1.448(0.006)	1.348(0.000)	1.742(0.095)
			CECOR	2.90	1.448(0.006)	1.344(-0.004)	1.747(0.100)
MOC	100% ARO	No	ECOMS	0.00	1.382(0.000)	1.201 (0.000)	1.505(0.000)
			CECOR	4.52	1.381(-0.001)	1.173(-0.128)	1.507(0.002)
		Max 10%	ECOMS	1.50	1.385(0.003)	1.199(-0.002)	1.591(0.086)
			CECOR	5.05	1.383(0.001)	1.170(-0.131)	1.591(0.086)
EOC	100% ARO	No	ECOMS	0.00	1.338(0.000)	1.125(0.000)	1.409(0.000)
			CECOR	3.69	1.338(0.000)	1.154(0.029)	1.410(0.001)
		Max 10%	ECOMS	1.54	1.349(0.011)	1.131(0.006)	1.456(0.047)
			CECOR	4.36	1.352(0.014)	1.160(0.035)	1.467(0.058)
EOC	70% Rod-in[d]	No	ECOMS	0.00	1.356(0.000)	1.236(0.000)	1.482(0.000)
		CECOR	4.00	1.355(-0.001)	1.251(0.015)	1.484(0.002)	
		Max 10%	ECOMS	1.58	1.361(0.005)	1.242(0.006)	1.539(0.057)
			CECOR	4.64	1.361(0.005)	1.258(0.022)	1.544(0.062)

[a] Values in parentheses is the difference with MASTER reference value(bold character)
[b] All Rod Out
[c] Normal distribution detector signal errors with the zero mean and 10% three sigma
[d] Regulating bank position : R5-63.1 cm, R4-292.1 cm

Table 2. Comparison of the 3D Peaking Factor Value

Burnup	Power CR	Signal Error	Fq			
			MASTER (Reference)	COLSS	CECOR	ECOMS
BOC	100%	No	1.951	2.220	2.217	1.951
	ARO	Max 10%		2.348	2.348	2.036
MOC	100%	No	1.646	1.808	1.768	1.646
	ARO	Max 10%		1.907	1.861	1.706
EOC	100%	No	1.538	1.586	1.627	1.538
	ARO	Max 10%		1.646	1.702	1.598
EOC	70%	No	1.707	1.831	1.856	1.707
	Rod-in	Max 10%		1.911	1.942	1.791

method.

As shown in Table 2, ECOMS agrees completely with the reference MASTER F_q values for cases without signal errors. Also, the values of the proposed method are a little more conservative than the reference values but are less conservative than the COLSS values when the random normal distribution signal errors are applied. Thus, the proposed method secures a larger operating margin than the current COLSS and CECOR methods.

Figure 1 compares the pseudo hot pin axial power distribution calculated by the COLSS and ECOMS methods, the best estimated axial power distribution of a *Fr* pin and the core average axial power distribution calculated by MASTER. The bumpy shapes of ECOMS pseudo hot pin axial power for the cases with signal errors are caused by the effect of random errors applied to the detector signals. Due to the random errors, the planewise peak $F_{xy}(z)$ arises at different pin positions rather than at the same pin. In all the calculation cases, the pseudo hot pin axial power distribution of the proposed method lies between the distributions of MASTER and COLSS. This shows that the pseudo hot pin axial power distribution of the proposed method is a more conservative value than the best estimated power distribution of the *Fr* fuel pin by MASTER, and that it also shows a less conservative value than that of the COLSS method. Thus, we can say that the pseudo hot pin axial power distribution of the proposed method ensures a greater operating margin than the pseudo hot pin axial power distribution of the COLSS method.

Table 1, Table 2, and Figure 1 show the result of a single case when one set of the random normal signal errors is applied, though this could be considered a special case because of the randomness. So, the 50 sets of random signal error distributions with a zero mean and 10 % three sigma (3σ=10 %, RMS$\approx$3 %) are generated and tested in the same manner and are applied to the simulated detector signals. Table 3 shows the simulation results of the 50 set power distributions derived from the 50 random normal signal error sets. As shown in Table 3, the mean of the RMS errors for 50 cases is about 1.6 % and the maximum of the RMS errors is below 1.9 % for all cases.

The computing time of the ECOMS is less than 0.05 seconds on the 1.8GHz PC machine but,

Table 3. Simulation Results of the Power Distribution with 50 Random Normal Signal Error Sets*

Burnup	Power CR	Power Distribution	Mean of RMS Errors (%)	Standard Deviation of RMS Errors (%)	Maximum of RMS Errors (%)	Minimum of RMS Errors (%)
BOC	100% ARO	3D Nodes	1.552	0.085	1.806	1.412
		2D Radial Assemblies	0.846	0.124	1.153	0.585
		1D Axial Planes	0.219	0.107	0.666	0.051
MOC	100% ARO	3D Nodes	1.559	0.081	1.791	1.426
		2D Radial Assemblies	0.798	0.115	1.122	0.507
		1D Axial Planes	0.248	0.123	0.728	0.056
EOC	100% ARO	3D Nodes	1.593	0.086	1.855	1.447
		2D Radial Assemblies	0.791	0.114	1.105	0.486
		1D Axial Planes	0.261	0.131	0.700	0.070
EOC	70% Rod-in	3D Nodes	1.622	0.093	1.911	1.465
		2D Radial Assemblies	0.807	0.114	1.121	0.530
		1D Axial Planes	0.264	0.138	0.700	0.049

*50 sets of normal distribution detector signal errors with the zero mean and 10% three sigma

when it includes the MASTER calculation, it then takes several seconds to complete the computations.

5. Conclusions

In this paper, a method of generating 3D power information for core monitoring coupled with the core design code is introduced. The proposed method was examined by purely numerical experiments for the core power distribution calculation in the YGN-3 Cycle-1, the first ABB-CE PWR in Korea. The proposed method exactly reproduces the reference power distribution and the power peaking factors when no signal errors are assumed. In all cases, the F_q value and the pseudo hot pin axial power distribution of the proposed method show slightly more conservative values than the reference values but they show less conservative values than those of the current CECOR and COLSS methods. Thus, it is confirmed that the developed methodology can secure a greater operating margin than the current CECOR and COLSS methods.

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