Core Follow Calculations for Hanbit Unit 3 Cycles 1 and 2 using the McCARD/MASTER code system

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1. Introduction

To improve a common two-step nuclear core analysis procedure, there has been a few studies on Monte Carlo (MC) method based Few Group Constants (FGC) generation [1-3]. It enables accurate and high-fidelity nuclear core analyses through the use of continuous energy cross section and the precise geometric information handling. Among the studies, Park and Shim established the McCARD based two-step core design code system. The McCARD can generate FGCs in the critical spectrum by solving multi-group B_1 equations, and its capability has been already verified through the single cycle nuclear core design analysis of a commercial PWR using McCARD/MASTER [4-5].

In this study, we will evaluate the core-following calculation capability of the McCARD/MASTER code system, with the ENDF/B-VII.1 library, by comparing it with deterministic code-based two-step analysis systems (i.e., CASMO/MASTER and DeCART2D/MASTER [6-7], also using the ENDF/B-VII.1), as well as with the nuclear design report (NDR) [8-9], through calculations for Cycles 1 and 2 of Hanbit Unit 3.

2. McCARD based Two-Step Procedure Code Systems

2.1. McCARD/MIG/MOCHA Code System

The McCARD based two-step procedure code system can generate input files and batch file for reference and branch calculations for the FGC generations through the MIG and MOCHA utilities. Figure 1 displays the flow chart of the code system. The MASTER code can conduct whole core calculations using the FGCs from the McCARD and MIG/MOCHA codes. The capability of MC based FGC generations has been verified in previous study [4].

Table. I. Reference and Branch Calculation Condition

Parameter	Calculation Condition	
	Reference	Branch
Boron Concentration (ppm)	500	1000
Fuel Temperature (kelvin)	900	700
Moderator Temperature (kelvin)	585	605, 565, 535, 485, 405, 295

Table I presents the conditions for reference and branch variation calculations for generating FGCs. For each fuel assembly (FA), FGCs were generated over 40 MWd/kgU. The number of depletion time steps (DTS) is 150. For each DTS, the McCARD calculations were performed using the 100 active cycles and 10,000 histories per cycle, resulting in a standard deviation of multiplication factor, k_{eff}, ranging from 60 pcm to 75 pcm. As this neutron history condition, it was assumed that the statistical error associated with core design parameters is negligible.

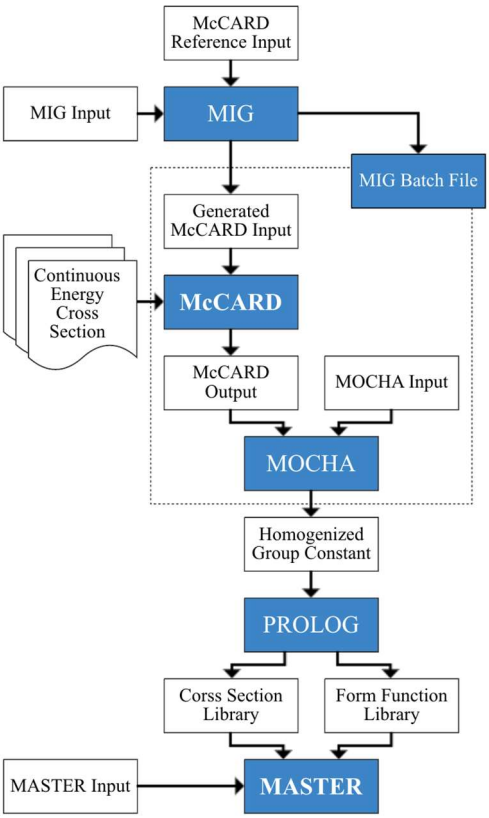

Fig. 1. Flow Chart of McCARD/MIG/MOCHA Code System

2.2. Specifications for Hanbit Unit 3 Cycles 1 and 2

In this study, the core following calculations for Hanbit Unit 3 during cycles 1 and 2 are calculated by McCARD/MASTER and compared with the results by the deterministic two-step procedure code system -

DeCART2D/MASTER and CASMO/MASTER. Hanbit Unit 3 is a 2815MWth PWR nuclear reactor located in South Korea, equipped with 177 FAs of the 16x16 Combustion Engineering type. During cycles 1 and 2, 12 types of FAs from A0 to E2 are loaded, among which B1, B2, C1, D1, D2, E1, and E2 FAs contain burnable poison rods. The burnable poison rods have burnable poison material only in the center, with the top and bottom ends having a cutback region without burnable poison material, for which FGC was separately generated. Table II and Figure 2 show the specifications of the fuel assemblies used in Cycles 1 and 2.

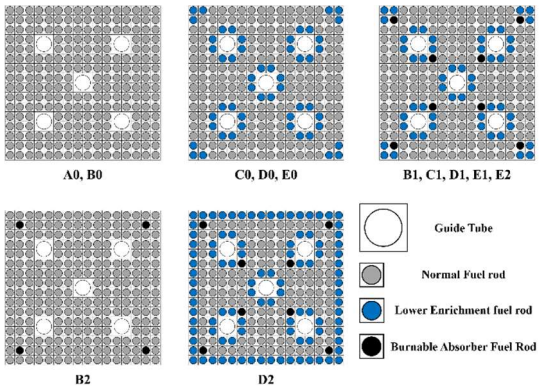

Fig. 2 Enrichment Zoning Pattern and Burnable Absorber Rod Arrangement

Table. II. Enrichment of Fuel Rod and Burnable Absorber (BA) content of BA rod (w/o)

FA Type	Enrichment (w/o)		FA Type	Enrichment (w/o)	
	Normal	Zoned		Normal	Zoned
A0	1.3	-	D0	3.3	2.8
B0	2.3	-	D1	3.3	2.8
B1	2.3	1.3	D2	3.3	2.8
B2	2.3	-	E0	4.0	3.6
C0	2.8	2.3	E1	4.0	3.6
C1	2.8	2.3	E2	3.6	3.1

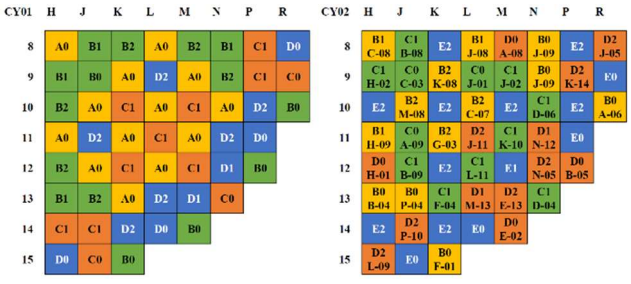

Fig. 3 loading pattern of Cycle 1 and Cycle 2

In multi-cycle operations, the isotope inventory of fuel assemblies used in the previous cycle is utilized for the analysis of the next cycle. Therefore, the loading pattern of the subsequent cycle must include the loading positions from the previous cycle. Figure 3 displays the loading patterns for Cycles 1 and 2.

3. Core Follow Calculation for Hanbit Unit 3

3.1. Critical Boron Concentration

Figures 4 and 5 show the critical boron concentrations (CBCs) for Cycles 1 and 2, respectively. The burnup calculations in Cycle 1 were performed over 13.65 MWd/MkgU, whereas it was conducted over 10.16 MWd/MkgU in Cycle 2, after 60 days of refueling. The results by the McCARD/MASTER code system were compared with the two deterministic codes, NDR, and measured data.

In Cycle 1, against the measurements, the root mean square (RMS) errors were about 25 ppm for CASMO/MASTER, 27 ppm for DeCART2D/MASTER, and 10 ppm for McCARD/MASTER. When compared to NDR, the errors were about 29 ppm, 28 ppm, and 8 ppm, respectively. For Cycle 2, based on NDR, the RMS Errors observed were 11 ppm for CASMO/MASTER, 18 ppm for DeCART2D/MASTER, and 35 ppm for McCARD/MASTER.

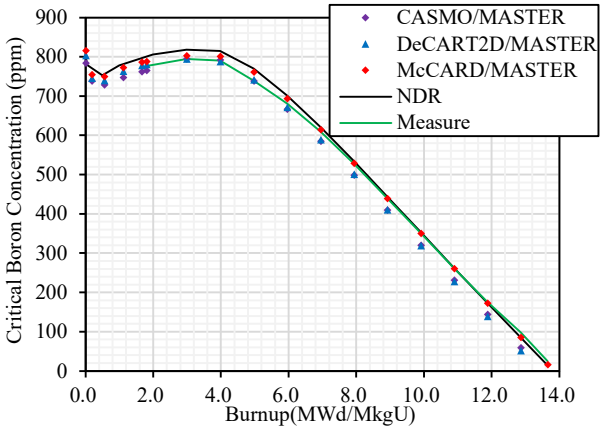

Fig. 4 Critical Boron Concentration of Cycle 1

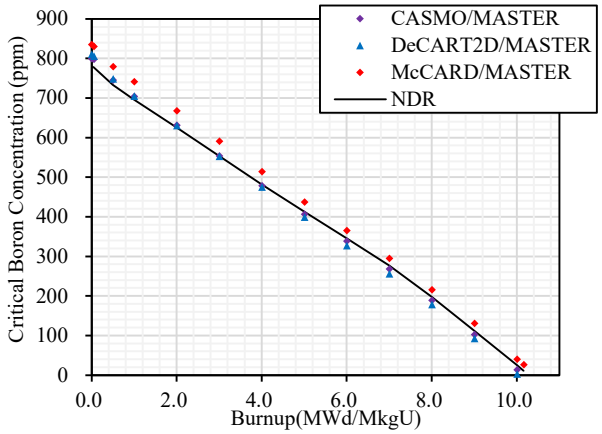

Fig. 5 Critical Boron Concentration of Cycle 2

3.2. Boron Worth and Temperature Coefficient

Table III shows the boron worth at the Beginning of Cycle (BOC) and End of Cycle (EOC) for Cycles 1 and 2, by CASMO/MASTER, DeCART2D/MASTER, and McCARD/MASTER, compared to the NDR. In comparison with the NDR, the boron worth (BW) of CASMO/MASTER, DeCART2D/MASTER, and McCARD/MASTER were underestimated by 5.45%, 3.58%, and 5.23%, respectively.

Table IV presents the moderator temperature coefficient (MTC) and fuel temperature Coefficient (FTC) calculated by the three two-step procedure code systems compared to the NDR. For MTC, the calculations were consistently higher by an average of 11.9%, 20.1%, and 17.6% compared to NDR. For FTC, CASMO/MASTER matched well within a 5% error rate, while DeCART2D/MASTER and McCARD/MASTER calculated lower by an average of -11.4% and -8.9%, respectively.

Table. III. Comparison of Boron Worth (BOC)

Code	Boron Worth (BW) (pcm/ppm)			
	Cycle 1		Cycle 2	
	BOC	EOC	BOC	EOC
NDR	-11.82	-12.08	-9.46	-10.75
CASMO/ MASTER	-11.47	-11.36	-8.99	-10.03
DeCART2D /MASTER	-11.53	-11.59	-9.13	-10.34
McCARD/ MASTER	-11.39	-11.45	-9.00	-10.09

Table. IV. Comparison of Temperature Coefficients

Case	Code	Temperature Coefficients (pcm/°C)			
		Cycle 1		Cycle 2	
		MTC	FTC	MTC	FTC
BOC	NDR	-8.74	-2.82	-21.91	-2.75
	CASMO/ MASTER	-10.22	-2.74	-23.65	-2.77
	DeCART2D /MASTER	-11.53	-2.54	-25.57	-2.43
	McCARD/ MASTER	-11.63	-2.37	-24.66	-2.54
EOC	NDR	-47.61	-2.90	-54.38	-2.90
	CASMO/ MASTER	-53.23	-2.92	-60.24	-3.04
	DeCART2D /MASTER	-55.39	-2.48	-62.68	-2.62
	McCARD/ MASTER	-53.30	-2.60	-61.25	-2.85

3.3. Power Peaking Factor and Power Distribution

Table V displays the node-wise and pin-wise power peaking factors, F_r, calculated by CASMO/MASTER, DeCART2D/MASTER, and McCARD/MASTER, alongside the values from NDR. It summarizes the node-wise and pin-wise peaking factors at BOC and EOC for Cycles 1 and 2. For the node-wise power peaking factor, all codes showed an error within 1% based on NDR, indicating good agreement. Regarding the pin-wise peaking factor, based on NDR, the maximum errors were 3.7% for CASMO/MASTER, 4.4% for DeCART2D/MASTER, and 1.7% for McCARD/MASTER.

Table. V. Comparison of Power Peaking Factors (F_r)

Case	Code	F_r			
		Cycle 1		Cycle 2	
		Node	Pin	Node	Pin
BOC	NDR	1.28	1.50	1.34	1.51
	CASMO/ MASTER	1.29	1.44	1.35	1.48
	DeCART2D /MASTER	1.29	1.45	1.34	1.46
	McCARD/ MASTER	1.29	1.48	1.34	1.50
EOC	NDR	1.26	1.35	1.36	1.51
	CASMO/ MASTER	1.26	1.34	1.36	1.45
	DeCART2D /MASTER	1.25	1.32	1.36	1.44
	McCARD/ MASTER	1.25	1.33	1.37	1.48

Table VI presents the RMS errors for the FA-wise radial power distribution, as calculated by CASMO/MASTER, DeCART2D/MASTER and McCARD/MASTER from the beginning of Cycle 1 (BOC) to the end of Cycle 2 (EOC), in comparison with the data from the NDR. And Figure 6 displays the FA-wise relative radial power distribution at the middle of cycle (MOC, 7.0 MWd/kgU) for Cycle 2, comparing the NDR data with the results from each code system. In comparisons with the NDR, all code systems calculated an RMS error between 1.0% and 2.0%.

Table. VI. RMS Errors of FA-wise Power Distributions

Code	RMS errors of FA-wise power distribution (%)					
	Cycle 1			Cycle 2		
	BOC	MOC	EOC	BOC	MOC	EOC
CASMO/ MASTER	2.0	1.1	1.2	1.1	1.1	1.0
DeCART2D /MASTER	1.5	1.0	1.5	1.2	1.1	1.1
McCARD/ MASTER	1.9	1.0	1.4	1.2	1.3	1.0

	1	2	3	4	5	6	7	8
A	FA Type					B0	E0	D2
	NDR					0.54	0.93	0.70
	CASMO					0.54	0.93	0.70
	DeCART2D					0.55	0.93	0.71
	McCARD					0.55	0.92	0.70
B				D0	E0	E2	D2	E2
				0.48	1.01	1.20	1.05	1.29
				0.50	1.01	1.18	1.04	1.26
				0.51	1.02	1.18	1.05	1.26
				0.51	1.01	1.17	1.04	1.25
C			C1	D2	D1	C1	B0	B0
			0.42	0.79	1.03	1.03	1.07	0.97
			0.43	0.79	1.02	1.03	1.06	0.96
			0.44	0.80	1.03	1.03	1.06	0.96
			0.44	0.80	1.03	1.03	1.06	0.96
D		D0	D2	E1	C1	E2	C1	D0
		0.49	0.79	1.29	1.02	1.38	1.04	1.12
		0.50	0.79	1.28	1.02	1.37	1.04	1.13
		0.51	0.80	1.28	1.01	1.36	1.04	1.12
		0.51	0.80	1.27	1.02	1.37	1.05	1.13
E		E0	D1	C1	D2	B2	C0	B1
		1.01	1.03	1.02	1.06	1.00	1.11	0.95
		1.01	1.02	1.02	1.06	1.01	1.11	0.96
		1.02	1.03	1.01	1.06	1.00	1.10	0.96
		1.01	1.03	1.02	1.07	1.00	1.11	0.96
F	B0	E2	C1	E2	B2	E2	B2	E2
	0.54	1.20	1.03	1.38	1.00	1.38	1.00	1.38
	0.54	1.18	1.03	1.37	1.01	1.38	1.02	1.38
	0.55	1.18	1.03	1.36	1.00	1.37	1.01	1.37
	0.55	1.17	1.03	1.37	1.00	1.37	1.01	1.37
G	E0	D2	B0	C1	C0	B2	C0	C1
	0.93	1.05	1.07	1.04	1.11	1.01	1.11	1.01
	0.93	1.04	1.06	1.04	1.11	1.02	1.13	1.03
	0.93	1.05	1.06	1.04	1.10	1.01	1.11	1.02
	0.92	1.04	1.06	1.05	1.11	1.01	1.12	1.03
H	D2	E2	B0	D0	B1	E2	C1	B1
	0.70	1.28	0.96	1.12	0.95	1.38	1.01	0.87
	0.70	1.26	0.96	1.13	0.96	1.38	1.03	0.90
	0.71	1.26	0.96	1.12	0.96	1.37	1.02	0.89
	0.70	1.25	0.96	1.13	0.96	1.37	1.03	0.89

Fig. 6 Assembly Wise Radial Power Distribution at MOC of Cycle 2

4. Conclusion

In this study, core follow calculations for Cycles 1 and 2 of Hanbit Unit 3 were performed using the MC based two-step analysis code system, McCARD/MASTER. The results for CBC, boron worth, FTC, MTC, power peaking factor and radial power distribution were compared with the two deterministic based two-step analysis code system (i.e., DeCART2D/MASTER, CASMO/MASTER), and NDR.

In the CBC calculations, the McCARD/MASTER code system presented improved calculation results compared to other codes, with an RMS error of 9.70 ppm based on the measurements and 8.27 ppm based on the NDR in Cycle 1. However, in Cycle 2, it exhibited an RMS error of 35.02 ppm when compared to the NDR, indicating some differences. Because the boron worth by McCARD/MASTER was 5.23% lower than the NDR, the results seem very reasonable from the perspective of excessive reactivity. Meanwhile, the MTC showed an error of 17.6%, and FTC showed -8.9%. During the two cycles, the power peaking factor closely matched the NDR. The power peaking factors by McCARD/MASTER agree well within 1% for node-wise tally and 1.7% for pin-wise tally. Simultaneously, the power distribution also showed good agreement with the NDR within 1.9%. Through this comparison, the core follow calculation capability of McCARD/MASTER was successfully verified.

In the near future, to evaluate the up-to-date nuclear data library, the McCARD/MASTER core follow calculations will be conducted using ENDF/B-VIII.0, JENDL-5.0, and TENDL-2021. And to confirm the uncertainties of nuclear core design parameters by the stochastic errors from MC FGC generations, uncertainty propagation analyses will also be performed during multi-cycles.

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