Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Republic of Korea, May 17-19, 2017

Shutdown Margin Analysis on the iPOWER Equilibrium Core according to the Control Rod Pattern

Jong-woo Lee*, Jeong-pyo Jeon , Jung-gyw Lee, Ki-bong Seong, Chae-joon Lim
Core Engineering Dept., KEPCO Nuclear Fuel, 989 Daedeokdae-ro, Yusung-gu, Daejeon 305-353, Republic of Korea
**Corresponding author: jongwoo@knfc.co.kr*

1. Introduction

iPOWER(innovative Passive Optimized Worldwide Economical Reactor) adapts passive safety system to improve nuclear power plant safety, which is currently in a conceptual design phase and the core and safety system is running parallel design. Thus RSDM(Required Shutdown Margin) is not decided yet. The operating domestic commercial nuclear plants have RSDM of 1.8 ~ 6.5 %$\Delta\rho$. Especially iPOWER core should guarantee the safety of the target, and there is a need to have a lager required SDM than existing nuclear power plants because of MOX fuel loading and load follow operation.[1][3]
For this reason, comprehensive SDM evaluation by changing control rod pattern is needed in iPOWER conceptual design phase.

This paper evaluates SDM based on control rod pattern and researches on the optimal SDM for the iPOWER equilibrium core. Furthermore the SDM according to control rod number and type are considered and the results are expected to be used in the iPOWER conceptual design analysis.

2. Definitions and Methods

2.1 Characteristic of iPOWER Core

The iPOWER is designed for 18 month equilibrium core and have 3572 MWt of core thermal power, 193 of fuel assembly and 14ft fuel height. The further characteristic of iPOWER core is given in TABLE 1.

Table 1. Characteristic of iPOWER core

Core Thermal Power	3572MWt
Number of Fuel Assembly	193 FAs
Number of Feed Fuel Assembly	68 FAs
Fuel Height	14 ft
Control rod material	Ag-In-Cd, B_4C

iPOWER core has eight fresh fuel assembly located on the outside of core. A quarter core loading pattern, indicating fresh and reloaded fuel assemblies is given in Figure 1.

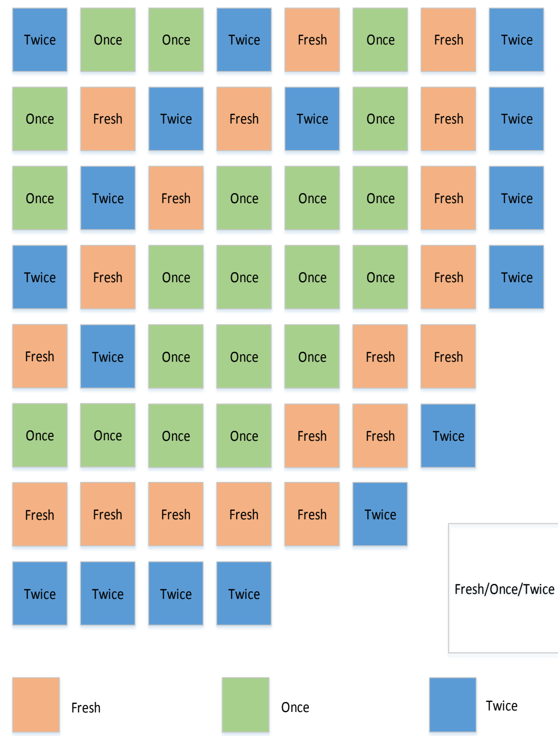

Figure 1. iPOWER equilibrium core loading pattern

2.2 Calculation of SDM

The SDM was calculated at EOC with the rod worth uncertainty, total power defect and void content are considered to get more limiting value. The RIL(Rod Insertion Limit) condition, and flux redistribution which are added to conservatism is not considered in this SDM calculation. The detailed calculation methodology is as follows.

$$\text{SDM calc(pcm)} = \ln\frac{k1}{k3} \times 10^5 \qquad (1)$$

$$\text{Rod worth uncertainty (pcm)} = 0.10 \times \ln\left(\frac{k2}{k3}\right) \times 10^5 \qquad (2)$$

$$\text{SDM true} = \text{SDM calc} - \text{Rod worth uncertainty} - 50\text{ pcm (for void)} \qquad (3)$$

Where,
K-effective at all rods out, hot zero power condition – k1
K-effective at all rods in – k2
K-effective at all rods in except the worst stuck rod – k3

2.3 Evaluation of iPOWER Control Rod Pattern

The total number of control rod varies from 53 to 81 with quarter-core cyclic symmetry. The arrangement of control bank is referred to the standard control bank location of the 193 assemblies core as shown in Figure 2. The evaluation for the control bank location is not considered, only shutdown bank location is modified.

The Ag-In-Cd has a long history of excellent performance in many commercial LWRs owe to its low swelling rate and good structural integrity as a function of irradiation. However Ag-In-Cd tends to have lower neutron worth than B_4C. Meanwhile the B_4C has neutron worth higher than other Ag-In-Cd even though B_4C is vulnerable to the swelling stress.[2]

The control rod type was basically Ag-In-Cd to evaluate the SDM. The SDM variation by changing the control rod Ag-In-Cd to B_4C and enriched B_4C is evaluated to get more SDM.

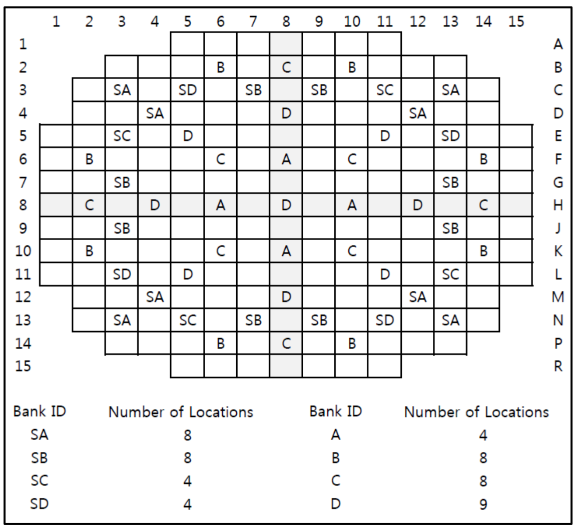

Figure 2. Control bank and shutdown bank reference arrangement

3. Results and Discussion

3.1 SDM depending on the number of Control Rod

The control rod arrangements used for calculating SDM are shown in Figure 3. Also the maximum and minimum SDM results which is evaluated with many cases are shown Figure 4. The amount of increase in the SDM according to the number of control rods decreases because of control rod shadowing effect.

The SDM deviation according to the patterns change is large if the number of control rod in core is small. Otherwise the control rod becomes full of core as the number of control rod increases. Therefore the change of pattern is limited and the SDM deviation according to the patterns change is small.

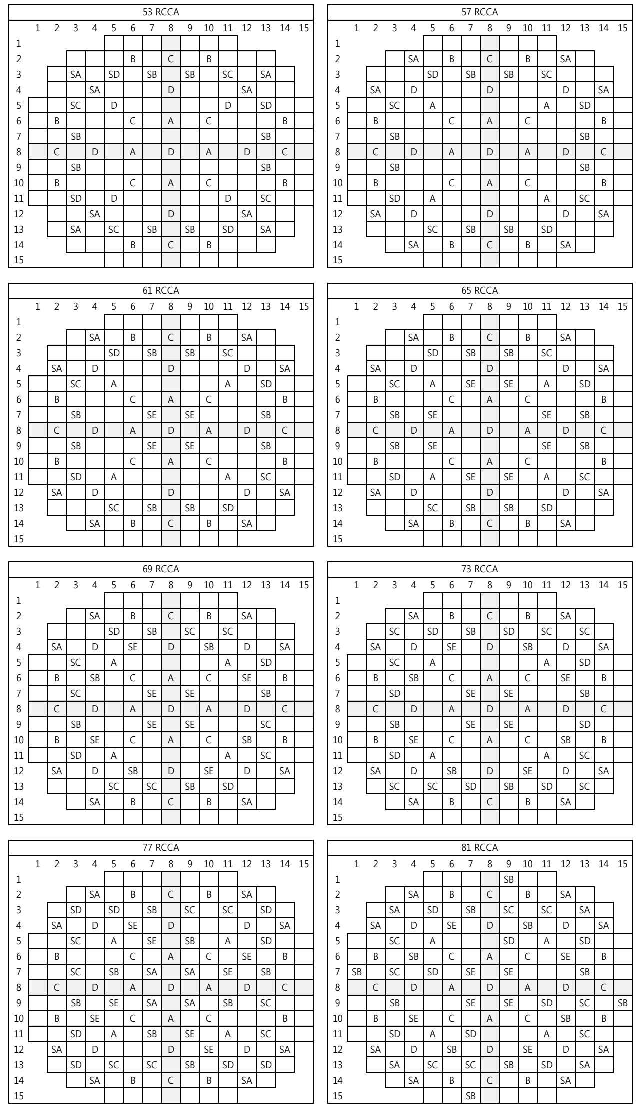

Figure 3. Control & shutdown bank arrangement for control rod number

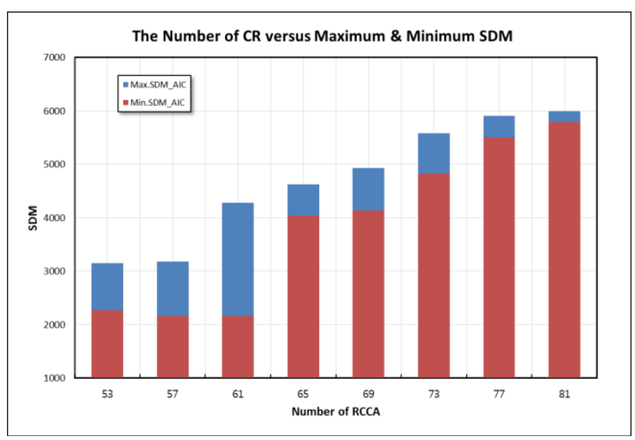

Figure 4. The Number of control rod versus maximum & minimum SDM

3.2 SDM Analysis for the Stuck Rod Worth

The maximum, average, standard deviation of the individual stuck rod worth and SDM and Deviation (Deviation with maximum SDM case and corresponding cases) results are given in Table 2.

Table 2. Statistical values for individual stuck rod worth

Number of CR		Max. (pcm)	Avg. (pcm)	Std. (pcm)	SDM (pcm)	Dev. (%)
53	case_1	1201	320	299	2269	28
	case_2	2391	843	727	2435	23
	case_3	1006	471	267	3150*	-
57	case_4	1045	352	299	3185*	-
	case_5	1564	405	489	2164	32
	case_6	2389	811	598	2643	17
61	case_7	1055	321	313	3196	25
	case_8	1060	658	274	4281*	-
	case_9	1599	368	511	2168	49
65	case_10	1638	906	483	4630*	-
	case_11	1669	865	517	4507	3
	case_12	2226	923	631	4041	13
69	case_13	2049	915	745	4654	-
	case_14	2241	857	625	4142	6
	case_15	1983	949	602	4932*	16
73	case_16	2677	556	795	5580*	-
	case_17	2063	861	621	4944*	11
	case_18	2155	717	853	4828	13
77	case_19	3187	1171	917	5508	4
	case_20	3083	1189	808	5731	3
	case_21	1742	688	472	5910*	-
81	case_22	3699	1275	1117	5826	3
	case_23	3130	1106	798	5789	3
	case_24	3051	1144	713	5995*	-

* The maximum SDM was marked

As shown in section 2.2 equation, a large SDM can be obtained, if the total control rod worths is large and calculated WSR(Worst Stuck Rod) worth is small. However as shown in table 2, the small standard deviation among the individual control rod worths gives a large SDM. In other words, if the more control rod worth is distributed evenly, the larger SDM could be obtained.

3.3 SDM Analysis depending on RCCA Type

Using advantages of B_4C about high neutron worth, additional SDM can be obtained by changing Ag-In-Cd to B_4C (using same control rods arrangement in 3.1). Also B_{10} enrichment in B_4C is increase 19.9 ~ 40.0 w/o to get more SDM. The results are given in Table 3.

Table 3. SDM for Ag-In-Cd, enriched B_4C

CR #	Control Materials					
	AIC	**B_4C^***	**B_4C_25**	**B_4C_30**	**B_4C_35**	**B_4C_40**
53	3150	3978	4118	4227	4318	4395
57	3185	4002	4141	4249	4338	4414
61	4281	5339	5505	5633	5739	5829
65	4630	5552	5676	5772	5852	5918
69	4932	5897	6051	6172	6272	6355
73	5580	6677	6851	6988	7099	7196
77	5910	7006	7178	7310	7420	7510
81	5995	7050	7215	7344	7450	7539

* B_{10} in B_4C natural abundance (19.90 w/o) was applied.

The SDM is increased by 17 ~ 26 % by changing control rod material from Ag-In-Cd to B_4C. Also the SDM is increased by 7 ~ 10 % by using enriched B_{10} in B_4C comparing 19.9 w/o B_4C results.

3.4 SDM Analysis for Hybrid control rod type

In section 3.3 all control rod are change from Ag-In-Cd to B_4C. However control rod of B_4C has swelling stress problem due to Helium release as depletion. Therefore there are constraint to apply iPOWER core Thus it is considered to apply different material for each bank as its own usage. In other words, control bank used during operation is composed of Ag-In-Cd, and the shutdown bank that are used only when shutdown is composed of B_4C. With this strategy, the additional SDM can be obtained compared to only Ag-In-Cd, and the integrity according to swelling of B_4C can be overcome. The SDM results for the hybrid Ag-In-Cd and B_4C is given in Table 4.

The SDM of hybrid Ag-In-Cd and B_4C control rod pattern is improved by 5 ~ 13 % comparing Ag-In-Cd results.

Table 4. SDM for Hybrid Ag-In-Cd & B_4C

Number of CR	AIC	AIC + B_4C^*	B_4C^*
53	3150	3303	3978
57	3185	3307	4002
61	4281	4710	5339
65	4630	4943	5552
69	4932	5489	5897
73	5580	6187	6677
77	5910	6680	7006
81	5995	6778	7050

* B_{10} in B_4C natural abundance (19.90 w/o) was applied.

4. Conclusions

The SDM of iPOWER core is calculated as a range from 3.2%$\Delta\rho$ to 7.5 %$\Delta\rho$ by changing control rod patterns as a following;

- Number of Control Rod : 53 ~ 81
- Control Rod Locations
- Material of Control Rod : Ag-In-Cd, B_4C, Enriched B_4C (25~40 w/o)

In consideration of advantage of B_4C, SDM is calculated by 7.0 %$\Delta\rho$ with combination of Ag-In-Cd and B_4C control rod pattern.

When the control rod pattern adopt the actual iPOWER core, the optimal SDM can be obtained by flattening the control rod worth as evaluated in section 3.2 can be found.

5. Future Plan

In this study, the analysis on variation of control bank was not covered. Since control bank is used during plant operation, there are a lot of things to consider. Therefore control rod pattern in accordance with actual plant operation condition should be studied in the future.

REFERENCES

[1] NRC, "MIXED-OXIDE FUEL USE IN COMMERCIAL LIGHT WATER REACTORS", U.S. Nuclear Regulatory Commission, Washington, DC, 1999.
[2] A. Strasser, et. al., "Control Rod Materials and Burnable Poisons", EPRI NP-1974, 1981.dia
[3] H. S. Lee, et. al., "APR1000 Core Design with 30% MOX Fuel Loading", Transactions of the Korean Nuclear Society Spring Meeting, 2011.