Analysis of the Axial Offset Anomaly of OPR1000

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1. Introduction

Much research has been conducted around the world since the first axial offset anomaly (AOA) phenomenon occurred in 1988. In June 2015, there was an axial offset anomaly in Korea. It caused a significant difference between the design axial shape index (ASI) and actual measured ASI.

In the case of OPR1000, the difference between the design ASI value and the measured ASI value tends to increase little by little. Therefore, there is a sufficient risk that AOA may occur. So, it is necessary to evaluate and analyze the AOA risk of OPR1000 before the AOA occurs, and reduce the AOA risk.

It is very important to find the optimal zinc injection time to lower the AOA risk since some OPR1000 plants have plans to perform zinc injection during operation. Therefore, in this study, AOA risk assessment is performed to find the optimal zinc injection time to reduce the AOA risk in OPR1000 which is performing zinc injection. The optimum zinc injection time will be analyzed through AOA risk assessment in $(N-1)^{th}$ and N^{th} fuel cycles.

2. Methods and Results

2.1 BOA modeling

The code used to analyze AOA risk is the BOA (Boron-Induced Offset Anomaly) code developed at the Electricity Power Research Institute (EPRI) [1]. The BOA code was developed to assess AOA risk. The analytical methods are as follows. For the AOA risk assessment, the plant design data and system operation conditions of the previous cycle are used as inputs, and the change of boron deposition amount according to the operation condition change such as reactor trip, steam generator replacement, zinc injection and ultrasonic cleaning is calculated. Then the amount of boron deposition amount is calculated and it is evaluated whether or not AOA occurs. The change in ASI is primarily due to the boron mass accumulated in the core, and the distribution of boron in the core plays a secondary role. EPRI sets the boron mass limit value for core conditions, which show a difference between the design ASI value and the measured ASI value, greater than 2% for the purpose of analyzing the AOA risk. The limit value is shown in Table I [2].

The AOA risk can be evaluated based on how much the maximum value of boron mass deposited in the core is. The boron mass predicted in the AOA core modeling of BOA code is an AOA indicator of the core. OPR1000 has 177 fuel assembly and as shown in Table I 0.28 lbm can be regarded as a limit to assess AOA risk. This limit is a criterion for evaluating the AOA risk of OPR1000 in this study and will be used as a very important value.

Table I: AOA Core Boron Mass for Various Core Sizes.

Core Size (# Assemblies)	121	157	177	193	217	241
Threshold for AOA (lbm)	0.19	0.24	0.28	0.30	0.34	0.37
Moderate AOA (lbm)	0.6	0.8	0.9	1.0	1.1	1.2
Severe AOA (lbs)	1.3	1.6	1.8	2.0	2.2	2.5

2.2 OPR1000 $(N-1)^{th}$ fuel cycle AOA assessment

Prior to the $(N-1)^{th}$ fuel cycle risk assessment of OPR1000, the ASI and AOA history of the previous cycles were examined. As a result of the operation tendency analysis, the power of the upper part started to be higher than that of the lower part at BOC in the case of the fuel cycles $(N-4)^{th}$, $(N-3)^{th}$, and $(N-2)^{th}$ of OPR1000, and the power of the lower part tended to be higher than that of the upper part at EOC.

To evaluate the AOA risk of OPR1000 $(N-1)^{th}$ fuel cycle, The version 3.1 of BOA code was used. And the characteristics of the loading pattern model of OPR1000 $(N-1)^{th}$ fuel cycle were confirmed. It had 69 new fuels, 108 reloaded fuels, and PLUS7 equilibrium cores. When performing BOA code, various input values can be set and analyzed in various ways, so the input values were set differently by dividing them into three cases and the code was performed.

In case 1, BOA code was performed assuming that zinc injection was not performed, ultrasonic cleaning was not performed, and there was no reactor trip. The results are shown in Table II. If the same operating conditions as the previous cycle are maintained, the maximum value of boron mass accumulated in the core is maintained within the AOA threshold limit (0.28

lbm) recommended by EPRI guidelines, indicating that there is no possibility of AOA occurrence. However, as a result of reflecting that the maximum value of $(N-2)^{th}$ fuel cycle, the maximum value of $(N-2)^{th}$ fuel cycle core boron mass was evaluated as 0.2835 lbm, exceeding the limit of AOA threshold limit (0.28 lbm) recommended by EPRI.

Table II: OPR1000 $(N-1)^{th}$ Fuel Cycle BOA Code Result (Case 1).

Case 1 : zinc injection not performed, ultrasonic cleaning not performed, and there was no trip					
Result \ Cycle	N-4	N-3	N-2	N-1	EPRI Threshold Limit
Maximum Core Boron Mass (lbm)	0.2858	0.2174	0.2835	0.2164	**0.28**
Maximum Crud Thickness (mils)	1.6147	1.6782	1.7550	1.7935	**3**
EOC Ni/Fe Ratio	1.9415	1.9634	1.9298	1.9076	**0.5 ~ 2.5**
EOC Ni Mass(lbm)	5.6727	5.9789	6.0700	6.0308	**N/A**

In case 2, the code was performed by assuming that zinc injection was performed, ultrasonic cleaning was not performed, and there was a trip once. The results are shown in Table III. When 5 ppb concentration of zinc was injected into $(N-1)^{th}$ fuel cycles without ultrasonic cleaning, the maximum value of core boron mass over the entire cycle exceeded the EPRI recommendation limit of 0.28 lbm, resulting in AOA. The main evaluation factors tended to increase as the zinc injection time approached the beginning of the cycle.

Table III: OPR1000 $(N-1)^{th}$ Fuel Cycle BOA Code Result (Case 2).

Case 2 : zinc injection performed(5ppb), ultrasonic cleaning not performed, and there was a trip once								
Result \ EFPD	Not	50	100	150	200	300	450	Result
Maximum Core Boron Mass (lbm)	0.2164	0.4234	0.4086	0.3922	0.3744	0.3383	0.3025	Max 0.21lbm increase
Maximum Crud Thickness (mils)	1.7935	2.1198	2.1029	2.0837	2.0628	2.0222	1.9677	Max 0.33mils increase
EOC Ni/Fe Ratio	1.9076	2.0412	2.0120	2.0121	1.9992	1.9795	1.8507	-
EOC Ni Mass(lbm)	6.0308	9.5417	9.4895	9.1806	8.9361	8.2554	7.0605	Max 3.51lbm increase

In case 3, code was performed by assuming zinc injection, spent fuel ultrasonic cleaning, and a trip once. The results are shown in Table IV. The maximum value of core boron mass exceeded the limit value of AOA (0.28 lbm) when zinc injection was performed before 150 EFPD, but the maximum value of core boron mass did not exceed the limit value of AOA when zinc injection was performed after 200 EFPD. If the ultrasonic cleaning of spent fuel is performed during the planned overhaul period, zinc injection is possible during the period from 200 EFPD to the end of the period.

Table IV: OPR1000 $(N-1)^{th}$ Fuel Cycle BOA Code Result (Case 3).

Case 3 : zinc injection performed(5ppb), ultrasonic cleaning performed, and there was a trip once								
Result \ EFPD	Not	50	100	150	200	300	450	Result
Maximum Core Boron Mass (lbm)	0.2164	0.3227	0.3065	0.2903	0.2731	0.2412	0.2093	Max 0.11lbm increase
Maximum Crud Thickness (mils)	1.7935	1.9523	1.9332	1.9121	1.8921	1.8506	1.7916	Max 0.16mils increase
EOC Ni/Fe Ratio	1.9076	2.0001	1.9678	1.9671	1.9548	1.9442	1.7962	-
EOC Ni Mass(lbm)	6.0308	10.0521	9.9909	9.6878	9.4171	8.6562	7.3985	Max 4.02lbm increase

2.3 OPR1000 N^{th} fuel cycle AOA assessment

The first step to evaluate the AOA risk of OPR1000 N^{th} fuel cycle was to analyze the tendency of the previous cycles [$(N-4)^{th}$, $(N-3)^{th}$, $(N-2)^{th}$, $(N-1)^{th}$]. The N^{th} fuel cycle AOA risk assessment was performed unlike $(N-1)^{th}$ fuel cycle AOA risk assessment. The version 3.1 of BOA code was used and the characteristics of the core loading pattern model were confirmed. It had 69 new fuels, 108 reloaded fuels, and PLUS7 equilibrium cores.

The code was assumed to have been performed zinc injection and ultrasonic cleaning similar to the actual situation of the N^{th} fuel cycle of OPR1000 when performing BOA code. The results are shown in Table V. When the spent fuel ultrasonic cleaning (cleaning efficiency: 40% assumption) was performed, the maximum core boron mass (0.1758 lbm) was not exceeded by the EPRI threshold limit (0.28 lbm) even after zinc injection after 50 EFPD at the beginning of the period.

Table V: OPR1000 N^{th} Fuel Cycle BOA Code Result.

Case : zinc Injection(5ppb) performed, ultrasonic cleaning performed, and there was a trip once								
Result \ EFPD	Not	50	100	150	200	300	450	Result
Maximum Core Boron Mass(lbm)	0.1592	**0.1758**	0.1722	0.1681	0.1583	0.1443	0.1249	Max 0.02lbm increase
Maximum Crud Thickness (mils)	1.7603	1.7821	1.7787	1.7730	1.7703	1.7477	1.7155	Max 0.02mils increase
EOC Ni/Fe Ratio	2.4655	2.2079	2.2065	2.2084	2.2091	2.2276	2.1746	-
EOC Ni Mass(lbm)	5.7523	8.3219	8.3219	8.2197	8.0931	7.6307	7.0065	Max 2.57lbm increase

3. Result and Discussion

As a result of the N^{th} fuel cycle AOA risk assessment of OPR1000, it was evaluated that the maximum value of core boron mass did not exceed the limit value of AOA recommended by EPRI even after zinc injection after 50 EFPD at the beginning of the cycle, and it was found that the possibility of AOA was low. The results of AOA risk assessment showed that zinc injection was possible after 50 EFPD.

Based on the zinc injection experiences of other plants, the best time of second zinc injection was conservatively evaluated as 100 EFPD after OPR1000 N^{th} fuel cycle startup.

4. Conclusions

Some OPR1000 plants plan to perform zinc injection during operation, and finding the optimal zinc injection time in the plants is a very important problem.

In this study, we conducted AOA risk assessment of $(N-1)^{th}$ and N^{th} fuel cycles in OPR1000 to investigate the optimal zinc injection time to reduce AOA risk. Zinc injection in N^{th} fuel cycle was found to be possible at the beginning of the cycle (50EFPD), unlike 200 EFPD in $(N-1)^{th}$ fuel cycle. This is the optimal zinc injection time for the economy and safety of the reactor and can be effectively used for zinc injection in OPR1000. This study showed that the second zinc injection can be performed at the beginning of the fuel cycle, which is a very meaningful result.

Since the deviation between the design ASI and the measured ASI is continuously increasing in OPR1000, careful monitoring is needed and zinc injection is required to be performed in accordance with the optimal time found by the AOA risk assessment.

REFERENCES

[1] Boron-induced Offset Anomaly Risk Assessment Tool (BOA) Version 3.1. EPRI, Palo Alto, CA: 2013. 3002000831.
[2] PWR Axial Offset Anomaly (AOA) Guidelines, Revision 1, EPRI, Palo Alto, CA: 2004. 1008102.