Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 29-30, 2015

Calculation for Estimated Criticality Point (ECP) with Enhanced Equation for Accurately Expecting RCS Boron-10 Ratio with Injection of Highly Concentrated Borated Coolant after Unplanned Reactor Shutdown

Ahn Sang-il [a*]
[a]*Korea Hydro & Nuclear Power Co.,Ltd.,*
[*]*Corresponding author: ahn.sangil@khnp.co.kr, khnpasi@gmail.com*

1. Introduction

To resume operation of a nuclear power plant (NPP) after unplanned reactor shutdown, an appropriate estimated criticality point (ECP) is previously calculated before approaching the reactor criticality. The abundance of boron-10 (B-10) has continuously decreased by its neutron absorption after starting operation of the reactor. Especially, as RCS B-10 ratio is the lowest at the end of a cycle during the cycle, B-10 ratio has remarkable deviation between reactor coolant system (RCS) and boron injection tank (BIT). Normally, when a reactor shuts unexpectedly down, from BIT, highly concentrated borated water with B-10 abundance which is almost same with natural boron's abundance should be injected to RCS to satisfy the shutdown margin required by the plant's technical specification. Mixing B-10 in RCS with the lowest abundance and B-10 in BIT with the highest (naturally occurring) abundance can make it difficult to accurately expect ECP prior to getting criticality of the reactor. Equation to predict B-10 ratio of RCS with several times of BIT coolant injection to RCS increases accurateness of calculating ECP for unplanned reactor shutdown.

2. Methods and Results

2.1 Current Way to Applying B-10 Ratio for Calculating Reactivity

As a core depletes, ratio of B-10 in RCS goes down from the natural abundance (nearly 20 a/o) at the beginning of a cycle (BOL) to a range of 15 a/o approximately at the end of a cycle (EOL). The abundances of the naturally occurring isotopes of boron are as follows:

- B-10: 19.90 %
- B-11: 80.10 %

Our interest in this paper is fully in B-10 because of its neutron absorption characteristic in terms of reactivity management. Under the technical information, NPPs in Korea periodically analyze B-10 ratio of RCS, BIT and RWST (Refueling Water Storage Tank) every 3 month to calculate core reactivity precisely. For reader's information, as equipment for measuring B-10 ratio is too expensive for all NPPs to have it, Korea Hydro & Nuclear Power has only one tool in Central Research Institute. NPPs have to send their boron samples to the research center by person. With the current B-10 analysis cycle, it has an intrinsic weakness for precise estimation of core reactivity. For example, let's assume RCS B-10 ratio was measured on January 1st and it will be measured again on April 1st with the current measurement plan. At the end of March, the plant is still using RCS B-10 ratio which is originally out-of-dated. Until updating new RCS B-10 ratio, NPPs use the previous B-10 value even though they know it's not an accurate B-10 ratio.

For quickly injecting negative reactivity into a core for some specific situations like unexpected reactor trip or possible accidents, BIT are storing boron with high concentration (above 7,000 ppm) and naturally occurring level of B-10 ratio (approximately 20.0 a/o). As mentioned before, during a core cycle, B-10 ratio would go down from 20 a/o at BOL to a range of 15 a/o at EOL. It means B-10 ratio deviation between BIT and RCS would be larger at EOL than at BOL. With assumption of occurring unplanned reactor shutdown at EOL, if a plant does not consider amount of coolant from BIT which is injected to satisfy shutdown margin in response to Mode change from Mode 1 (Power Operation) to Mode 3 (or 4, 5), the plant will have remarkable ECP prediction error for being calculated to resume reactor operation. The more injected coolant from BIT or the higher burnup of reactor within one cycle length, the bigger discrepancy of B-10 ratio between RCS and BIT.

2.2 Case Study for Kori unit 2 Cycle 27

Kori unit 2 started its operation for its 27th cycle on July 17, 2013 and it shut unexpectedly down on August 25, 2014 as heavy rain was flooded with a crucial pump room. The burnup was 16,458 MWD/MTU at that time with the design burnup 20,040 MWD/MTU which is normally considered as EOL. It took a month for the completion of maintenance since then. Mode changed from Mode 1 to Mode 5. Basic information related to boron is described the Table I below

Table I: Basic information for boron at the shutdown time

Item	B-10 Ratio	Concentration
RCS	16.74 a/o	457 ppm
BIT A*	19.00 a/o	7,227 ppm
BIT B*	19.14 a/o	7,215 ppm
BIT average	19.07 a/o	7,221 ppm

* Kori unit 2 has two BITs like BIT A and BIT B.

Considering that if some amount of BIT coolant is injected to RCS, then same amount of existing reactor coolant will be discharged out of RCS for volume balance, we can calculate B-10 ratio in RCS, like Table Ⅱ.

Table Ⅱ: Calculating estimated B-10 ratio in RCS

Item	Value
Kori unit 2 RCS mass volume (ⓐ)	112.2 ton
Amount of injected BIT coolant (ⓑ)	21.1 ton
RCS boron concentration before shutdown (ⓒ)	457 ppm
Average BIT boron concentration (ⓓ)	7,221 ppm
Measured average BIT B-10 ratio (ⓔ)	19.07 a/o
Measured RCS B-10 ratio before shutdown (ⓕ) – measured date: June 23rd, 2014	16.74 a/o
Estimated RCS B-10 ratio measurement (ⓖ)	18.57 a/o
Deviation between measured and estimated RCS B-10 ratio (ⓖ−ⓕ)	1.83 a/o (11 % ↑)

Estimated RCS B-10 ratio measurement (ⓖ) is calculated to 18.57 a/o by using following equation (1) and the data in Table Ⅱ:

$$ⓖ = \frac{ⓑ\times ⓒ\times ⓔ+(ⓐ-ⓑ)\times ⓓ\times ⓕ}{ⓑ\times ⓒ+(ⓐ-ⓑ)\times ⓓ} \qquad (1)$$

Kori unit 2 calculated ECP using estimated RCS B-10 ratio measurement (ⓖ). The way to normally calculate ECP is to fix the control rod position and search RCS boron concentration. The plant operator asked a domestic fuel provider, KEPCO Nuclear Fuel (KNF) to decide proper control rod position given the reactor characteristics and power ascension scenario after getting criticality. KNF provided the plant with the control bank position, Control Bank ‘D’ 90 Step for criticality. According to Kori unit 2’s nuclear design report (NDR) for 27th cycle, differential boron worth was – 7.702 pcm/ppm with RCS boron concentration 1,004 ppm, RCS temperature 291.7 ℃ (Mode 3, hot standby) and the burnup (16,458 MWD/MTU). Predicted critical point data was estimated including RCS B-10 ratio. Table Ⅲ shows comparison results between measured and predicted critical point data (in predicted data, there is modified RCS B-10 ratio and unmodified RCS B-10 ratio that ‘modified’ means RCS B-10 ratio is compensated with the amount of injected coolant to RCS from BIT and an ‘unmodified’ RCS B-10 ratio does not consider it).

Table Ⅲ: Calculating estimated B-10 ratio in RCS

Case	Control Rod		RCS Boron		Deviation sum (pcm)	Criteria (within ± 500 pcm)
	Position* (step)	Deviation** (step) (pcm)	Concentration (ppm)	Deviation (ppm) (pcm)		
Measured	151	N/A	1,004	N/A	N/A	N/A
Predicted (modified)	90	+ 61 + 357	976	+ 28 - 216	+ 141	satisfied
Predicted (unmodified)	90	+ 61 + 357	1,082	- 78 + 601	+958	unsatisfied

* Position: control bank ‘D’ location
** Deviation: measured - predicted

Table Ⅲ shows reflecting amount of injected coolant from BIT to RCS is essential for predicting accurate critical point. Unless considering amount of injected coolant from BIT to RCS, Table Ⅲ demonstrates ECP result may not meet the criteria that between measured and predicted ECP result would be within ± 500 pcm. After approaching criticality, the Chemistry Department gets RCS sample to identify how equation (1) is effective to predict RCS B-10 ratio with several times of irregular injection of BIT coolant to RCS. Difference between measured and predicted RCS B-10 ratio which is - 0.05 a/o (0.3 %) demonstrates the accurateness and effectiveness of the equation (1) [1].

Table Ⅳ: Measured and predicted RCS B-10 ratio at Kori unit 2 for 27th cycle

Methodology	RCS B-10 Ratio	Date	Burnup (MWD/MTU)
Measured	16.74 a/o	June 23rd 2014	13,894
Predicted	18.57 a/o	Sep. 24th, 2014	16,458
Measured	18.52 a/o	Sep. 24th, 2014	16,458

This is the first time to get samples to compare measured and predicted RCS B-10 ratio to identify the effectiveness of the prediction methodology (equation (1)). Sufficient numbers for proving the accurateness and effectiveness of this methodology are still needed. Table Ⅴ is the reason not to get, send and analyze RCS B-10 ratio at that time. An answer for a possible question is in Table Ⅴ as follows:

Table Ⅴ: Reason Not to analyze RCS B-10 ratio

Q: Why did not Kori unit 2 analyze B-10 ratio of RCS right before achieving criticality? It is normally believed measuring current B-10 ratio is the best way for calculating reactivity. A: While the reactor shut down, plant operators have continuously injected BIT coolant to RCS with the change of MODE and plant situations. In other words, it is not easy to decide the timing of final RCS B-10 sample during the reactor shutdown. As no NPPs have B-10 ratio measurement tools, B-10 samples have to be sent to the research center that taking at least 2 days.

3. Conclusions

Equation (1) is the useful tool to predict B-10 ratio of RCS with several times of irregular injection of BIT coolant to RCS that increases accurateness of calculating ECP for getting criticality when unplanned reactor shutdown occurs. This is certified by actual B-10 analysis data of RCS sample and demonstrated very low estimation error (0.3 %) [1].

4. REFERENCES

[1] KHNP Research Center, B-10 Analysis Report, KHNP, Daejon, 2014