Evaluation of the Kinetic Characteristics of a Soluble Boron-Free BANDI Core for Main Steam Line Break Accident Analysis

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1. Introduction

Soluble boron-free (SBF) core designs are being actively investigated for small modular reactors (SMRs) to reduce plant size by simplifying the chemical and volume control system (CVCS), decrease liquid radioactive waste, and prevent boric acid-induced corrosion. In South Korea, the innovative SMR (i-SMR) is a representative example under development, and KEPCO Engineering & Construction (KEPCO E&C) is also independently developing the BANDI core, an SMR adopting this SBF concept.

Compared to conventional pressurized water reactors (PWRs), an SBF core fundamentally possesses a significantly larger negative moderator temperature coefficient (MTC). This provides the advantage of drastically enhancing the inherent safety of the reactor by inserting a strong negative reactivity during abnormal moderator heat-up accidents. Conversely, in overcooling scenarios where heat removal by the secondary system rapidly increases, such as a main steam line break (MSLB) accident, this strong negative MTC can induce a massive positive reactivity insertion into the core.

Therefore, to investigate the impact of these kinetic characteristics on the MSLB analysis, the BANDI core was evaluated using the GPU-based Monte Carlo code PRAGMA [3]. Furthermore, this study aims to highlight the methodological differences in the kinetic analysis for MSLB safety evaluation between the SBF core and large commercial PWRs, such as the APR1400, particularly in establishing the initial accident conditions and analysis data.

2. Method and Conditions for Kinetics Evaluation

2.1 Target and Scope of Kinetics Analysis

The target of this study, the BANDI-60, is an SMR with a thermal capacity of 200 MWth currently under development by KEPCO E&C [1, 2]. It consists of 52 Westinghouse-type 17×17 fuel assemblies using 4.95% enriched UO_2 fuel and employs a single-batch operation concept with no refueling. Furthermore, to control excess reactivity and ensure a sufficient shutdown margin in an SBF operating environment, the core features a design that utilizes five types of assemblies loaded with Pyrex-based burnable absorbers (BAs) alongside a total of 40 control element assemblies (CEAs).

The scope of the kinetics analysis was established by varying the following key conditions:

- **Core Burnup:** Beginning of cycle (BOC, 0 effective full power days [EFPD]), intermediate of cycle (IOC, 50 EFPD), middle of cycle (MOC, 1000 EFPD), and end of cycle (EOC, 1585 EFPD).
- **Power Level:** Hot full power (HFP) and hot zero power (HZP) states.
- **CEA Insertion Position:** All rods out (ARO), critical rod position (CRP), all rods in (ARI), and an ARI(N-1) condition (assuming the most reactive single CEA is stuck out of the core to ensure conservatism in the safety analysis).
- **Xenon (Xe) Condition:** Equilibrium xenon (Eq. Xe) and no xenon (No Xe) states.

Ultimately, for each core state derived from the combinations of these conditions, the kinetic parameters, moderator temperature coefficient (MTC), fuel temperature coefficient (FTC), and CEA SCRAM worth were evaluated.

2.2. Core Analysis Code and Calculation Conditions

The GPU-based Monte Carlo code PRAGMA and the ENDF/B-VII.1 nuclear data library were utilized for the kinetics calculations. While conventional CPU-based Monte Carlo codes impose a significant burden when exploring numerous operating conditions due to the massive computational resources and time required for kinetics analysis, the recently introduced GPU-based code drastically reduces computational costs through large-scale parallel processing. This enables the kinetics analysis of a vast array of conditions within a practical timeframe.

The core depletion calculation was performed by simulating the CRP at each burnup point under HFP conditions, considering the depletion effects of not only the fuel but also the CEAs inserted into the core. Based on the material composition data generated for each burnup point (IOC, MOC, EOC), the kinetics evaluation was conducted through restart calculations while maintaining identical material compositions. Although thermal-hydraulic (T/H) feedback was applied to the HFP conditions, the reactivity calculations corresponding to changes in moderator and fuel temperatures were evaluated by uniformly applying the respective average temperatures of the moderator and fuel across the core. The results of the CRP searches, which define the specific core states according to the burnup, power level, and xenon conditions, are summarized in Fig 1., Tables 1 and 2.

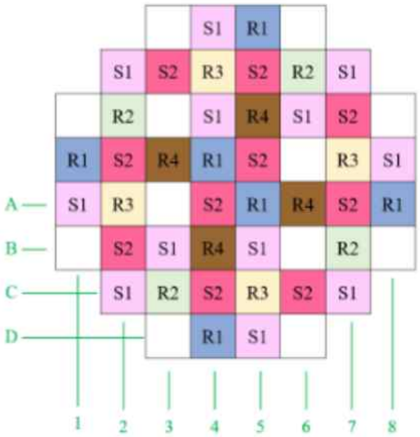

Fig. 1. Configuration of CEAs

Table1. Information about CEAs

Type	Number of CEAs	Role
R4	4	Regulating
R3	4	
R2	4	
R1	6	
S2	10	Primary Shutdown
S1	12	Secondary Shutdown
Total CEAs	40	-

- CEAs insertion sequence: R4→R3→R2→R1
- The CEA bank overlap is set to 20cm, corresponding to 10% of the effective core height.

Table 2. CRPs under Various Core Conditions.

Burnup Step	CEA inserted Length [cm]			
	HFP		HZP	
	Eq. Xe	No Xe	Eq. Xe	No Xe
BOC	-	R4: 200 R3: 111 R2: 0 Sum: 311	-	R4: 200 R3: 200 R2: 77 Sum: 477
IOC	R4: 107 R3: 0 R2: 0 Sum: 107	R4: 200 R3: 91 R2: 0 Sum: 291	R4: 200 R3: 76 R2: 0 Sum: 276	R4: 200 R3: 188 R2: 8 Sum: 396
MOC	R4: 130 R3: 0 R2: 0 Sum: 130	R4: 200 R3: 113 R2: 0 Sum: 313	R4: 200 R3: 96 R2: 0 Sum: 296	R4: 200 R3: 200 R2: 44 Sum: 444
EOC	R4: 0 R3: 0 R2: 0 Sum: 0	R4: 130 R3: 0 R2: 0 Sum: 130	R4: 113 R3: 0 R2: 0 Sum: 113	R4: 200 R3: 78 R2: 0 Sum: 278

3. Kinetic Characteristics of the BANDI Core

3.1 Shutdown Margin and SCRAM Characteristics

When calculating the reactor shutdown margin (SDM), the ARI(N-1) condition is applied, which assumes that the single control element assembly (CEA) with the highest reactivity worth is completely stuck out of the core. As shown in Fig. 1, the BANDI core features a point-symmetric layout of CEA groups. Evaluating the SDM for each stuck CEA position revealed that the most conservative scenario (i.e., the minimum SDM) occurs when the B7 assembly, belonging to the R3 regulating bank, is stuck across all explored core states. Although the R3 bank is operated in a partially inserted state (critical rod position, CRP) to maintain criticality depending on the core conditions, the state where the B7 CEA is stuck at the all-rods-out (ARO) position was established as the reference condition for ARI(N-1) to ensure conservatism in the safety analysis.

The scram worth was calculated as the total amount of negative reactivity inserted from the CRP to the ARI(N-1) state, excluding the worth of the CEAs already inserted to maintain criticality. These results are presented in Table 3. In the MSLB accident analysis, the fraction of the total negative reactivity inserted as a function of the CEA insertion depth is a critical factor. This reactivity insertion profile depends heavily on the axial power distribution. In an SBF core, CEAs are inserted from the top of the core to control excess reactivity; therefore, at the BOC, where a relatively large number of CEAs are deeply inserted, a highly bottom-skewed Axial Shape Index (ASI) is formed. The ASIs for each core state are summarized in Table 4. and Table 4. Consequently, at BOC, the available shutdown CEA worth is relatively low due to the influence of the pre-inserted CEAs. The scram worth as a function of the CEA insertion depth under specific ASIs is shown in Fig. 2.

Table 3. Scram Worth

Burnup Step	CEA inserted Length [%Δρ]			
	HFP		HZP	
	Eq. Xe	No Xe	Eq. Xe	No Xe
BOC	-	-18.97(0.01)	-	-17.73(0.01)
IOC	-21.35(0.01)	-19.16(0.02)	-20.23(0.01)	-18.27(0.01)
MOC	-22.65(0.01)	-20.45(0.01)	-21.30(0.01)	-19.22(0.01)
EOC	-26.04(0.01)	-23.64(0.01)	-24.46(0.01)	-22.09(0.01)

3.2 Moderator and Fuel Temperature vs. Reactivity

According to the steady-state MTC evaluation of the BANDI core, the most negative MTCs at both HFP and HZP (e.g., -196.17±3.62pcm/°C and -172.90pcm/°C) were observed under the EOC, ARI, and Eq. Xe conditions.

Table 4. ASI Various Core Conditions.

-	BOC		MOC		EOC
	CRP	ARO	CRP	ARO	ARO
ASI (RSD)	0.495 (0.95%)	0.217 (0.78%)	0.303 (0.80%)	0.178 (0.77%)	0.214 (0.74%)

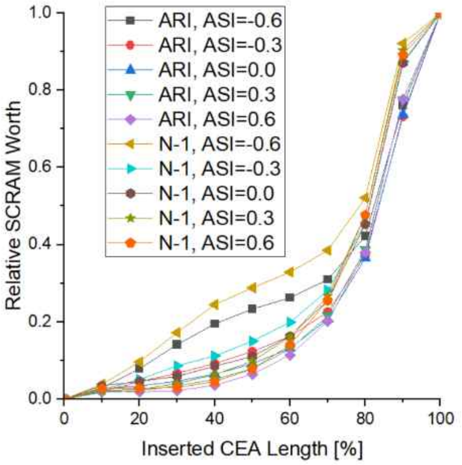

Fig. 2. Normalized Axial Power Distribution

An MSLB accident involves a wide range of temperature drops in the primary system due to secondary-side overcooling. As the moderator cools, the MTC becomes less negative. Therefore, applying a single constant MTC value obtained from HFP or HZP conditions across the entire accident transient would result in an overly conservative calculation of positive reactivity insertion. To mitigate this excessive conservatism in the MSLB analysis, the reactivity change as a function of the moderator temperature was derived in the form of a table/curve and applied to the safety analysis, as shown in Fig. 3.

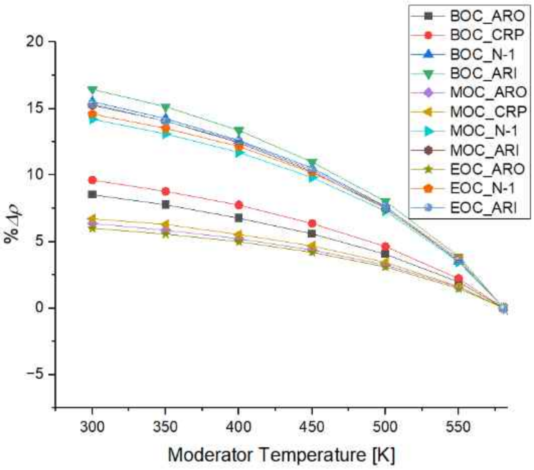

Fig. 3. Moderator Temp. vs. Reactivity

Regarding the fuel temperature coefficient (FTC), the most negative value was similarly observed under the EOC and ARI conditions. The reactivity change according to the fuel temperature variation at the EOC is illustrated in Fig. 4.

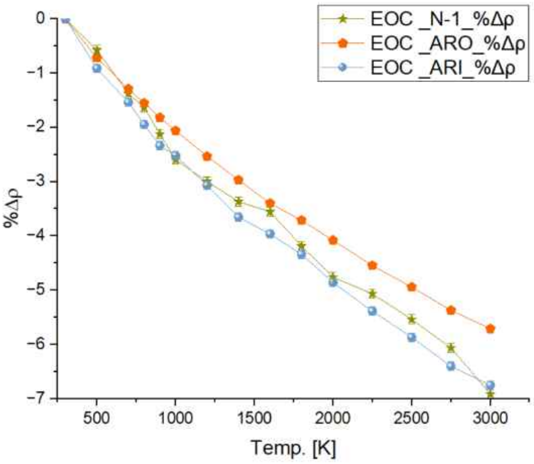

Fig. 4. Fuel Temp. vs. Reactivity at the EOC

3.3 Effective Delayed Neutron Fraction

The calculated effective delayed neutron fractions are presented in Figs. 5. It is observed that the effective delayed neutron fraction consistently decreases as the core burnup progresses and as the CEAs are further inserted into the core.

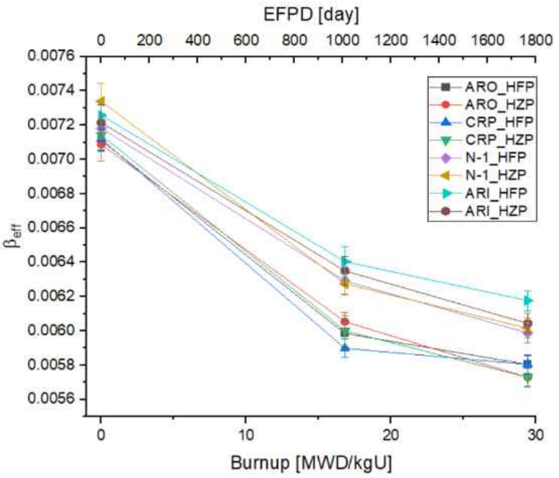

Fig. 5. Fuel Temp. vs. Reactivity

4. Conclusions

In conventional large PWRs, the MSLB analysis focuses on two main aspects: preventing fuel damage prior to a reactor trip and preventing re-criticality after the trip. From both perspectives, the bounding scenario for an MSLB in a large PWR is generally established at the end of the cycle (EOC), when the soluble boron concentration is extremely low, causing the MTC to become severely more negative. However, for an SBF core, these two aspects must be evaluated separately depending on the burnup stage.

First, at BOC, the ASI is highly bottom-skewed, and the available shutdown reactivity is low due to the deeply pre-inserted CEAs required for criticality.

Considering these factors alongside the absence of a xenon defect, the possibility of post-trip re-criticality must be carefully considered. (The shutdown margins of the BANDI core under CZP, ARI(N-1), and No Xe conditions are summarized in Table 5.) Conversely, at EOC, the power distribution is top-skewed, and the pre-inserted CEA depth is shallow, resulting in a significantly high available shutdown CEA worth. Therefore, the probability of re-criticality at EOC is evaluated to be lower than at BOC.

Table 5. Shutdown Margin at CZP, ARI(N-1), No Xe conditions.

-	BOC	MOC	EOC
Shutdown Margin (SD) [pcm]	-1623.86(8.67)	-2297.61(8.03)	-4259.12(7.07)

Nevertheless, at EOC, the possibility of fuel damage prior to the reactor trip cannot be ruled out due to the highly negative MTC and the low effective delayed neutron fraction. On the other hand, while the MTC at BOC is less negative than at EOC, it is still significantly more negative compared to conventional large PWRs. This strong negative MTC, combined with the delayed insertion of shutdown reactivity caused by the initial CEA positions, suggests a high potential for fuel damage during the early transient phase.

Future studies will focus on quantitative accident analyses to thoroughly investigate these transient phenomena.

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