Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 22-23, 2025

Audit Calculation for the Burnup Effect on OPR1000 LBLOCA Analysis

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1. Introduction

Nuclear fuel burnup has steadily increased, and recently ongoing issues such as extending fuel cycle and increasing fuel enrichment have led to a growing demand for high burnup operation. Therefore, it is necessary to reassess the emergency core cooling system (ECCS) criteria by considering high burnup fuel characteristics, which were not addressed in the past. Along with this, computational codes for ECCS performance evaluation have evolved, incorporating burnup effects in recent studies.

The vendors introduce a new core modeling approach for system thermal-hydraulic analysis considering the burnup effect [1]. Unlike the conventional method, which models the core with a hot rod, a hot channel, and an average channel, the new approach reflects a three-batch fuel cycle. It categorizes fuel into fresh, once-burned, and twice-burned. Accordingly, burnup-dependent thermal conductivity and gap gas composition are applied. KINS has conducted independent audit calculations using the MARS-KS code for OPR1000 LBLOCA analysis. Although not a legal requirement, these calculation results can be utilized as supporting materials for the technical review of ECCS performance.

This paper presents the modification of the MARS-KS code core modeling to account for burnup effects. Based on this, the LBLOCA base calculation was performed considering the number of burnup cycles. Additionally, uncertainty calculations were conducted using the KINS-Realistic Evaluation Methodology (KINS-REM) [2,3] to determine whether the peak cladding temperature (PCT) meets the acceptance criteria.

2. Modification of MARS-KS core modeling

For the LBLOCA analysis, the thermal-hydraulic channels and heat structures of the core were modified in the MARS-KS code node configuration of the OPR1000 to reflect the burnup effects. The reactor core comprises four thermal-hydraulic channels: one average core channel and three hot channels. The three hot channels are designed to exchange heat with fresh fuel, once-burned fuel, and twice-burned fuel, respectively. Each hot channel includes two heat structures, one for the hot rod and the other for the remaining hot channel (assembly) average rods. The average core channel models all fuel rods, except for the three hot rods and the three hot channel average rods, by categorizing them into three groups based on the number of burnup cycles. The modified core modeling is presented in Fig. 1 and summarized in Table 1.

The bypass flow was adjusted due to the addition of hot channels, resulting in a total bypass flow of 3%, which is the target value in the core design. Additionally, to reflect thermal characteristics, parameters such as power distribution, thermal conductivity, initial oxide thickness, rod internal pressure, and gap gas composition, which the vendor provides, were categorized and applied by heat structure, respectively.

Fig. 1. Modified core modeling of MARS-KS

Table 1: Configuration of the OPR1000 core modeling

	Classification	Modified node
Thermal-hydraulic channels (4)	Average core channel	Average core channel (150)
	Hot channel	Fresh (160)
		Once (161)
		Twice (162)
Heat structures (9)	Average core rods (Ave chn)	Fresh
		Once
		Twice
	Hot channel average rods (Hot chn)	Fresh
		Once
		Twice
	Hot rod (Hot pin)	Fresh
		Once
		Twice

3. Assessment of burnup effects in OPR1000 LBLOCA analysis

3.1 Calculation conditions

Except for core modeling, the primary system of the OPR1000 nuclear power plant adopted the same node configuration as used in previous studies [4]. Additionally, the steady-state and transient analysis input data for the LBLOCA scenario remained unchanged except for core thermal-hydraulic channel and heat structure modifications.

The vendor-provided power distribution reflected the reduction in power due to the depletion of fissile material as burnup increased. The power distribution was configured to follow a cosine shape, with higher power concentrated in the central axial region, and was designed to encompass the neutronics data. The core consists of 12 axial nodes, which differs from the 40 nodes used in the vendor's calculations.

3.2 Discussion on burnup effect on PCT

The OPR1000 LBLOCA base calculation results reflecting the modified core modeling are demonstrated in Fig. 2. It represents the cladding temperature at the mid-height of the fuel (node 6), where the power is highest. It was observed that the PCT of the twice-burned hot pin (Hot pin(Twice)) is lower than that of the once-burned hot channel (Hot chn(Once)). This dose not seem a typical result, because the hot pin is usually more conservatively modeled than the hot channel average rods. However, it can be considered reasonable since it reflects the power reduction associated with burnup cycles.

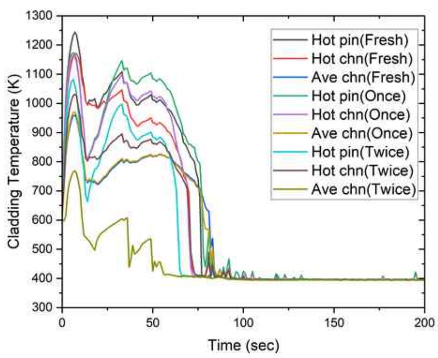

Fig. 2. Cladding temperature calculation results for OPR1000 during the LBLOCA

In the cases of the hot pin and hot channel, the blowdown PCT was generally higher for fresh fuel than for multi-burned fuel. However, as shown in Fig. 3, the average core rods exhibited a different trend, where the blowdown PCT of once-burned fuel was analyzed to be higher than that of fresh fuel. Although the once-burned fuel had lower power and lower initial cladding temperature, the change in gap gas composition due to fuel depletion was the primary factor contributing to a higher PCT compared to fresh fuel. As illustrated in Fig. 4, the gap gas composition used in this analysis considered the decrease in the molar fractions of He, Ar, and N_2 with increasing burnup, while the molar fractions of fission gases Xe and Kr increased accordingly. This reflects the phenomenon where the gap is initially filled with He at the beginning of the cycle but accumulates fission gases such as Xe and Kr as the depletion progresses. Since Xe and Kr have lower thermal conductivity compared to other gases and the initial gap size was set uniformly, it was observed that the deterioration of heat transfer in the gap led to an increase in PCT. If the fresh fuel gas composition were applied to the other multi-burned heat structures, thereby isolating the effects of burnup-dependent gap gas composition changes, the blowdown PCT of once-burned fuel decreased by approximately 15 K, as shown in Fig. 5. This trend was consistently observed in both the hot pin and hot channel average rods cases.

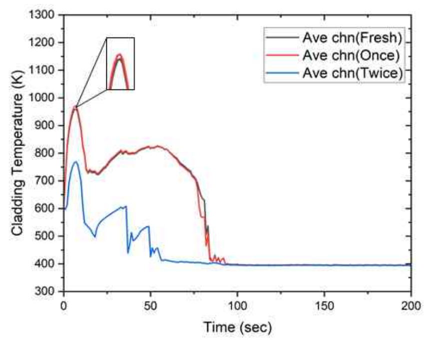

Fig. 3. Cladding temperature of average core rods by burnup

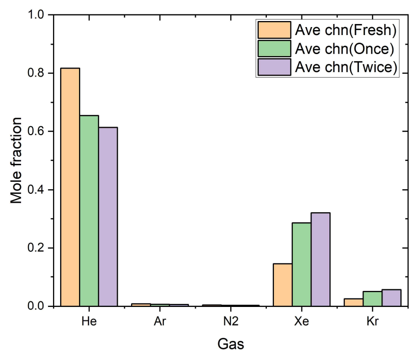

Fig. 4. Gap gas composition of average core rods by burnup

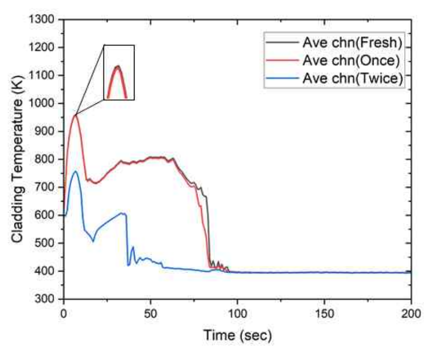

Fig. 5. Cladding temperature of average core rods with the same fresh fuel gap gas composition

In actual nuclear fuel behavior, the fuel-cladding gap size decreases with fuel depletion; however, this analysis does not account for such effects. If the gap size reduction is considered, the impact of changes in gas composition may become insignificant. In addition, pellet thermal conductivity significantly affects the PCT, and thermal conductivity degradation (TCD) is observed with increasing burnup in practice. However, in this calculation, the same pellet thermal conductivity was applied to all heat structures except for fresh fuel in hot pin and hot channel average rods, as depicted in Fig. 6. As a result, it is limited to quantitatively evaluate the impact of burnup-induced pellet TCD on the PCT.

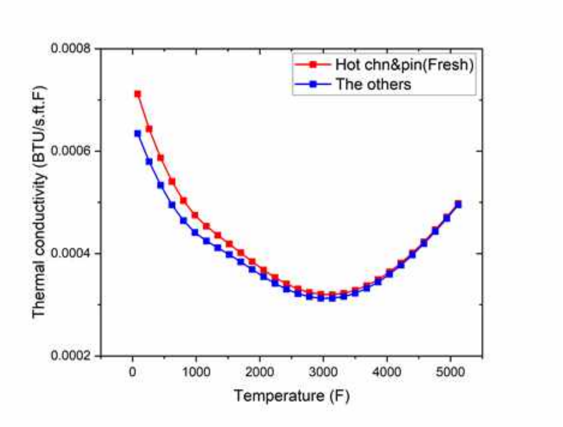

Fig. 6. Simplified thermal conductivity degradation

4. Uncertainty analysis of LBLOCA in OPR1000

4.1 Determination of uncertainty variables and distribution

The uncertainty calculation is based on the well-established KINS-REM; determining the range and distribution of uncertainty variables is crucial. In LBLOCA calculations for pressurized water reactors (PWRs), the inherent uncertainty of the code itself and the predictive uncertainty arising from initial and boundary conditions play a significant role. These conditions include core power, nuclear fuel parameters, coolant pump operation, safety injection systems, and system parameters such as pressure and flow rate.

Numerous studies [4-8] have extensively evaluated the significant phenomena associated with LBLOCA in PWRs. Therefore, in this study, the analysis was conducted using the MARS-KS code based on the range and distribution of uncertainty variables used in previous verification studies employing the KINS-REM.

The uncertainty variables and their distributions are summarized in Table 2. A total of 124 simple random sampling (SRS) processes were conducted based on the range and distribution of 18 uncertainty variable combinations. The 124 calculations were statistically determined using the third-order Wilks formula, where the third-highest PCT (3rd PCT) value obtained from these calculations represents the $PCT_{95/95}$ with a 95% probability and 95% confidence level [9]. This value is then used to verify compliance with the acceptance criteria.

Table 2: Uncertainty variables and distribution

No.	Variables	Distribution
1	Gap conductance (cladding roughness)	Normal
2	Fuel conductance	Uniform
3	Core power	Normal
4	Decay heat	Normal
5	Groeneveld CHF Dial	Normal
6	Chen Nucleate Boil Dial	Normal
7	T_{Min} Dial	Uniform
8	Dittus Boelter liquid Dial	Normal
9	Dittus Boelter vapor Dial	Normal
10	Bromley Dial	Normal
11	Break CD	Normal
12	Pump Head Multiplier	Uniform
13	Pump torq Multiplier	Uniform
14	SIT Pressure(lbf/in^2)	Uniform
15	SIT water Vol(ft^3)	Uniform
16	SIT water Temp(F)	Uniform
17	SIT line K factor	Uniform
18	RWST water Temp(F)	Uniform

4.2 Results of uncertainty analysis

The results of 124 calculations of the cladding temperature during LBLOCA are shown in Fig. 7. In all cases, the cladding temperature in the fresh hot pin was the highest among the nine heat structures. Moreover, the blowdown PCT was higher than the reflood PCT; in most cases, each PCT occurred at 7 and 32 seconds, respectively. The base case calculation result was approximately in the middle of the 124 calculation results, confirming that the calculation was appropriately performed. The 3rd PCT was confirmed to be 1,332.5 K, which satisfies the ECCS acceptance criteria below 1,477 K (1,204 ℃).

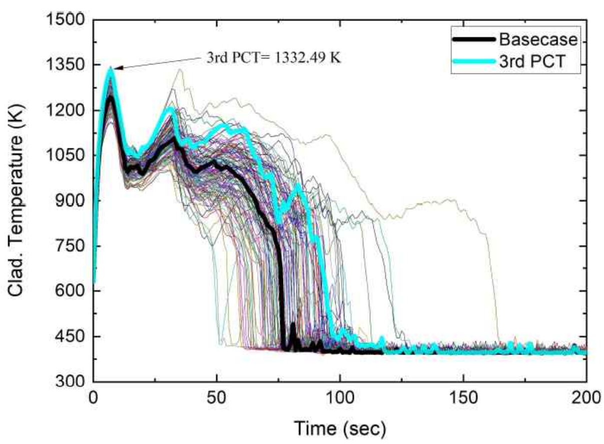

Fig. 7. Results of 124 uncertainty calculations of cladding temperature in hot pin (fresh fuel)

The following factors primarily ensured the conservatism of the audit calculation.

- Core power distribution: The core power is set within the range of 0.98 to 1.02 by applying a 2% error, which is also considered an uncertainty under the conservative evaluation method (10 CFR 50 Appendix K) [10]. However, in this study, considering that the power peaking factor (Fq) was applied as a constant at its mean value of the uncertainty range used in vendor's calculations, a more conservative approach was taken by determining it as a normal distribution with a range of 1.00 to 1.02.
- Fuel parameter: The gap conductance is important in determining the stored energy of the fuel, which is the primary heat source in the LBLOCA scenario. The gap conductance was conservatively estimated by setting the cladding roughness approximately eight times higher than in the vendor's calculations.

5. Conclusions

This study modified the MARS-KS core modeling to incorporate burnup effects in the OPR1000 LBLOCA analysis. By separating the heat structures and channels of the reactor core based on the number of burnup cycles, burnup effects can be incorporated into thermal-hydraulic and material properties.

With burnup effects considered, the PCT in a less burned hot channel was found to be higher than in a more burned hot pin. This is due to changes in power and heat transfer characteristics within the fuel, such as pellet thermal conductivity and gap gas composition, as burnup increases.

The uncertainty calculations were performed using the KINS-REM methodology. Compared to the vendor's calculations, the higher PCT value was obtained due to the conservative assumptions, such as stricter core power and increased cladding roughness. Despite this, it was confirmed that the ECCS acceptance criteria were still satisfied.

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