Sensitivity Analysis of Operator Actions in Bleeding Timing in OPR-1000 and APR-1400

Gangmin Kim[1], Jaewhan Kim[2], Jaehyun Cho[3*], Changhyun Jang[4]

[1]*Chung-Ang University, Heukseok-ro 84, Dongjak-gu, Seoul, 06974, Republic of Korea,* kkm371837@cau.ac.kr
[2] *Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon, 34057, Republic of Korea,* jhkim4@kaeri.re.kr
[3] *Chung-Ang University, Heukseok-ro 84, Dongjak-gu, Seoul, 06974, Republic of Korea,* jcho@cau.ac.kr
[4]*Chung-Ang University, Heukseok-ro 84, Dongjak-gu, Seoul, 06974, Republic of Korea,* ckdguso@cau.ac.kr

ABSTRACT

This study presents a comprehensive sensitivity analysis of operator actions during feed-and-bleed operations in OPR-1000 and APR-1400 nuclear reactor types under Small Break Loss of Coolant Accident (SBLOCA) conditions. The SBLOCA event tree and the sequence leading to Feed-and-Bleed (F&B) operation for OPR-1000 and APR-1400 were constructed based on the probabilistic safety assessment (PSA) methodology and plant-specific accident analysis reports [1]. Using the MARS-KS thermal-hydraulic code, we analyzed the time margins available for operator intervention between Steam Generator (SG) Wide Range (WR) level reaching 2% and the necessity to initiate bleeding operations to prevent core damage. The analysis was conducted across various break sizes ranging from 0.5 to 2.0 inches. Results demonstrate significant differences in available response times between the two reactor designs, with OPR-1000 consistently providing longer time margins (9,100-16,000 seconds) compared to APR-1400 (5,500-15,200 seconds) for equivalent break sizes. For larger break sizes (>0.8 inches in OPR-1000 and >1.2 inches in APR-1400), the analysis revealed that bleeding operations become unnecessary as the break itself provides sufficient depressurization. These findings have important implications for Emergency Operating Procedures (EOPs) and operator training programs, suggesting that APR-1400 requires more stringent response protocols and potentially different decision-making criteria compared to OPR-1000. The study contributes valuable insights for enhancing nuclear safety by optimizing operator response strategies based on reactor-specific time constraints.

Keywords: feed and bleed, emergency operating procedure, SG wide range, SBLOCA

I. Introduction

I.A. Background

Small Break Loss of Coolant Accident (SBLOCA) in nuclear power plants occurs due to a break in the Reactor Coolant System (RCS), which can lead to core damage if not properly managed. The severity of a SBLOCA depends on the break size, location, and the effectiveness of emergency response systems. In Korean nuclear power plants, particularly OPR-1000 and APR-1400 designs. Figure 1 is a visualization of the SBLOCA event tree highlighting the sequence that leads to Feed and Bleed (F&B) operation, illustrating key decision points from Small Break LOCA initiation to successful primary depressurization and ECCS injection.

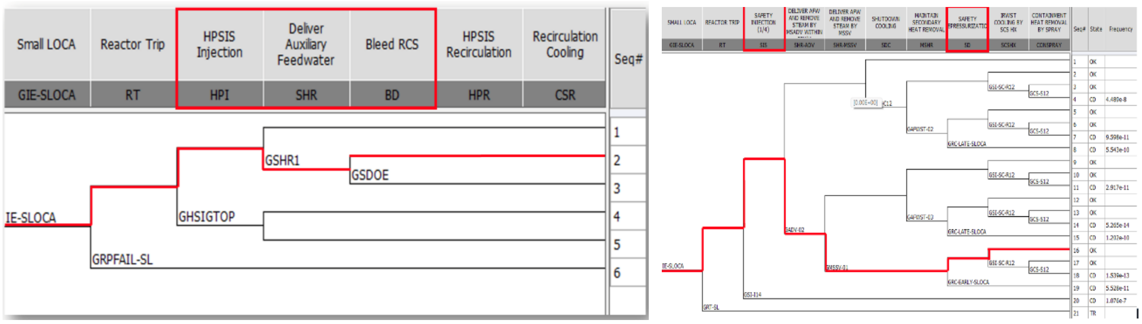

FIGURE 1. OPR-1000, APR-1400 SBLOCA Event Tree

I.B. Feed and Bleed Operation

F&B operation is a critical cooling strategy employed when normal heat removal pathways fail during accidents like SBLOCA. This operation involves depressurizing the reactor vessel by opening primary safety valves (SDS Valve in OPR-1000, POSRV in APR-1400) to release steam and injecting cooling water through the Emergency Core Cooling System (ECCS). When the primary system pressure decreases sufficiently, Safety Injection (SI) is activated to sustain core cooling, ensuring the removal of decay heat from the reactor core and preventing excessive temperature rise.

The successful implementation of F&B operations heavily depends on operator decision-making and response time. When the Steam Generator (SG) Wide Range (WR) level drops below 2%, operators must manually open the primary system safety valves to release steam. The SG WR level is a measurement signal that continuously monitors the water level over a broad span within the steam generator, taking into account the specific geometry and design of the SG. This parameter seves as a crucial indicator for assessing the available inventory of coolant, especially during emergency operations, since a drop below 2% WR level signals a significant depletion of water and necessitates prompt operator action. According to the Emergency Operating Procedures (EOP) for Shin-Kori 3 and 4, operator-initiated bleeding should be performed when the Steam Generator (SG) Wide Range level drops below 2% [2]. This study aims to analyze the impact of bleeding time and operator intervention on core damage prevention during SBLOCA in OPR-1000 and APR-1400 reactors, specifically focusing on determining the timing at which operators open the valves upon receiving the F&B signal and analyzing the effect of operator intervention delays on cooling performance and core integrity.

I.C. Research Objectives

This study aims to analyze the impact of bleeding time and operator intervention on core damage prevention during SBLOCA in OPR-1000 and APR-1400 reactors1. Specifically, the research focuses on:

1. Determining the timing at which operators open the valves upon receiving the F&B signal when the SG WR level falls below 2%
2. Analyzing the effect of operator intervention delays on cooling performance and core integrity
3. Comparing the time margins available for operator action between OPR-1000 and APR-1400 reactor designs
4. Developing recommendations for optimizing Emergency Operating Procedures based on reactor-specific time constraints

II. Methodology

The MARS-KS code was used for thermal-hydraulic system analysis of the SBLOCA scenarios. The accident scenario follows a specific sequence: Reactor Trip, Safety Injection, Auxiliary Feedwater (AFW) failure, and RCS Bleeding. In the OPR-1000 scenario, after Reactor Trip (RT), the High Pressure Safety Injection (HPSI) successfully operates, followed by the failure of the AFW. In the APR-1400 scenario, after RT, safety injection is successfully initiated, followed by AFW failure, successful opening of the Main Steam Safety Valve (MSSV), but ultimately, the secondary heat removal fails. Figure 3 is a schematic illustrating the key SBLOCA mitigation sequence from reactor coolant system breach and AFW failure to SG WR level dropping below 2%, Feed-and-Bleed valve actuation, and subsequent ECCS injection to maintain core cooling.

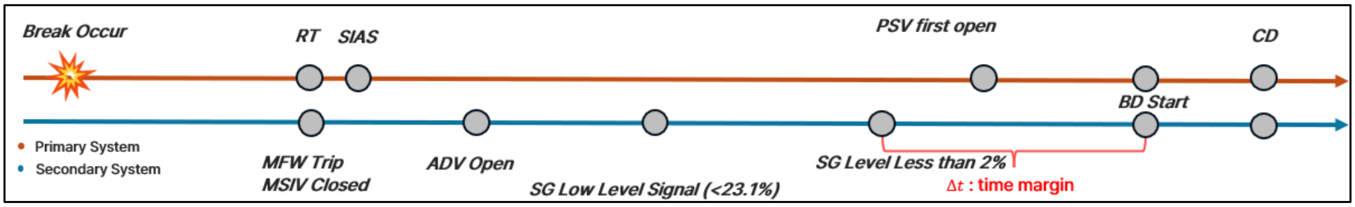

FIGURE 3. Emergency Operating Procedures (EOP) of APR-1400

II.A. Sensitivity Analysis Approach

This study analyzed break sizes ranging from 0.5 to 2.0 inches in 0.1-inch intervals to comprehensively evaluate the effect of break size on F&B operation performance. This range was selected based on the definition of SBLOCA in safety analysis reports and previous studies that identified these sizes as most critical for emergency responses evaluation. The incremental approach allowed for detailed analysis of the transition points where operator intervention becomes critical or unnecessary.

When the SG WR level reaches 2%, the valve open signal is generated, and sensitivity analysis was conducted by delaying the valve open time in 100-second intervals. The objective was to determine the maximum allowable time margin before core damage, defined as a peak cladding temperature (PCT) exceeding 1477K.

II.B. Time Margin Definition and Calculation

This approach enabled the identification of the critical time window available for operator action in each reactor type and for each break size. Time margin (Δt) is defined as the maximum allowable time between the SG WR level dropping below 2% and the initiation of bleeding, without leading to core damage. This margin represents the operator's available response time before the situation escalates to an irreversible state. The calculation involved determining the time at which the SG WR level reached 2% and then incrementally delaying the bleeding initiation until the PCT reached the critical threshold of 1477K. Figure 4 illustrates the operator time margin and core damage indicators during a OPR-1000 0.5-inch SBLOCA event: the left plot shows Steam Generator wide-range level decline and valve mass flow rate over time, highlighting the delay between SG level dropping below 2% and valve actuation; the right plot displays peak cladding temperature trends, indicating the point of core damage threshold (1477 K) when the time margin is exceeded.

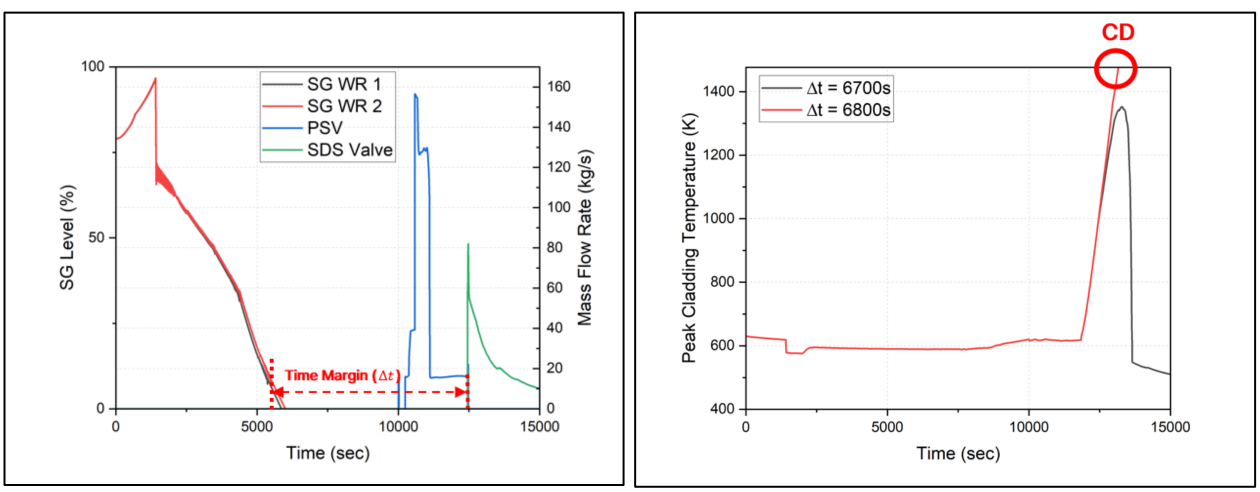

FIGURE 4. Major Operating Variables and Cladding Temperature Response in OPR-1000 SBLOCA Event

III. Results

III.A. OPR-1000 Time Margin Analysis

For OPR-1000, the analysis revealed significant time margins for operator intervention across various break sizes. The maximum allowable time margins were 9,100 seconds for a 0.5-inch break, 9,100 seconds for a 0.6-inch break, 11,000 seconds for a 0.7-inch break, and 16,000 seconds for a 0.8-inch break. For break sizes larger than 0.8 inches, the analysis showed that bleeding operations become unnecessary as the break itself provides sufficient depressurization to enable effective safety injection.

TABLE I. Results of OPR-1000 Analysis

Trip Signal	0.5[in]	0.6[in]	0.7[in]	0.8[in]
PZR low pressure signal	1,410s (24min)	925s (15min)	655s (11min)	492s (8min)
ADV open	2,310s (39min)	1,825s (30min)	1,555s (26min)	1,392s (23min)
SG low level signal	2,515s (42min)	2,194s (37min)	1,923s (32min)	1,760s (29min)
SG WR level 2[%]	2,789s (46min)	2,399s (40min)	1,948s (32min)	1,782s (30min)
PSV First Open	8,426s (140min)	8,773s (146min)	10,619s (177min)	15,443s (257min)
Bleeding Point	11,889s (198min)	11,499s (192min)	12,948s (216min)	17,782s (296min)
time margin (Δt)	**9,100s (152min)**	**9,100s (152min)**	**11,000s (183min)**	**16,000s (267min)**

III.B. APR-1400 Time Margin Analysis

APR-1400 exhibited shorter time margins compared to OPR-1000 across all analyzed break sizes. The maximum allowable time margins were 5,500 seconds for a 0.5-inch break, 5,600 seconds for a 0.6-inch break, 6,700 seconds for a 0.7-inch break, and 7,800 seconds for a 0.8-inch break. The time margin continued to increase with break size, reaching 15,200 seconds for a 1.2-inch break. For break sizes larger than 1.2 inches, bleeding operations were found to be unnecessary.

TABLE II. Results of APR-1400 Analysis

Trip Signal	0.5[in]	0.6[in]	0.7[in]	0.8[in]	0.9[in]	1.0[in]	1.1[in]	1.2[in]
PZR low pressure signal	2,888s (48min)	1,988s (33min)	1,445s (24min)	1,102s (18min)	871s (15min)	707s (12min)	588s (10min)	499s (8min)
ADV open	3,788s (63min)	2,888s (48min)	2,345s (39min)	2,002s (33min)	1,771s (30min)	1,607s (27min)	1,488s (25min)	1,399s (23min)
SG low level signal	6,511 (109min)	5,925s (99min)	5,470s (91min)	5,449s (91min)	5,618s (94min)	5,852s (98min)	6,120s (102min)	6,543s (109min)
SG WR level 2[%]	7,429s (124min)	7,155s (119min)	6,852s (114min)	6,929s (115min)	7,149s (119min)	7,528s (125min)	7,949s (132min)	8,689s (145min)
PSV First Open	9,792s (163min)	9,935s (166min)	10,458s (174min)	11,059s (184min)	12,233s (204min)	13,947s (232min)	16,535s (276min)	22,436s (374min)
Bleeding Point	12,929s (215min)	12,755s (213min)	12,522s (209min)	12,929s (215min)	13,849s (231min)	15,328s (255min)	17,949s (299min)	23,889s (298min)
time margin (Δt)	**5,500s (92min)**	**5,600s (93min)**	**5,700s (100min)**	**6,000s (112min)**	**6,700s (130min)**	**7,800s (130min)**	**10,000s (167min)**	**15,200s (253min)**

III.C. Comparative Analysis Between Reactor Types

The comparative analysis reveals that OPR-1000 consistently provides longer operator time margins than APR-1400 for equivalent break sizes. For example, at a 0.5-inch break, the maximum allowable time margin (Δt) for OPR-1000 is approximately 9,100–16,000 seconds (152–267 minutes), while for APR-1400 it is 5,500–15,200 seconds (92–253 minutes). On average, OPR-1000 offers about 1.4 times more response time than APR-1400. This difference is primarily attributed to design characteristics such as larger primary system volume, higher safety injection capacity, and more effective decay heat removal in OPR-1000 compared to APR-1400. The differences in time margin between OPR-1000 and APR-1400 are primarily attributed to their design characteristics, including primary system volume and safety injection capacity, as discussed in previous feasibility analyses [3]. Figure 5 shows the evolution of primary system pressure and safety injection mass flow rates during SBLOCA, highlighting the timing of HPSI/DVI injection limits and the onset of effective safety injection for OPR-1000 and APR-1400, respectively.

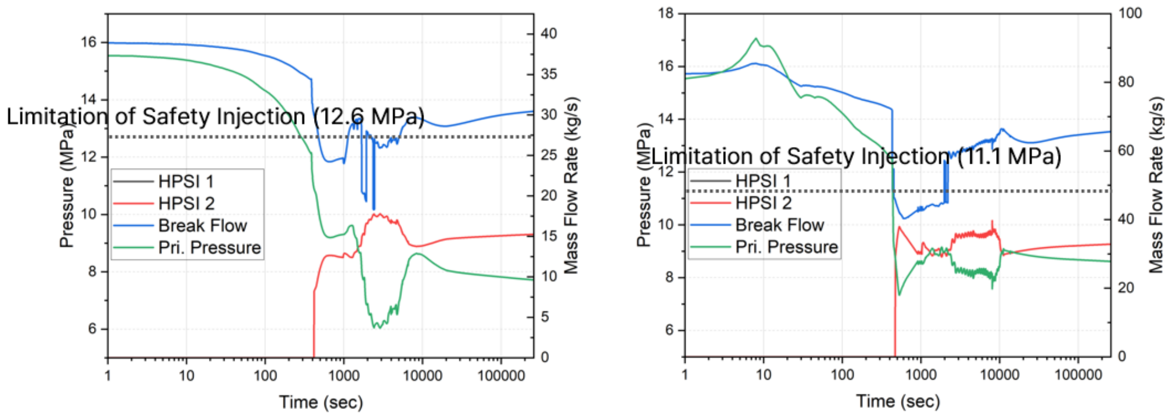

FIGURE 5. Primary System Pressure and Safety Injection Mass Flow Rate During SBLOCA for OPR-1000 (left) and APR-1400 (right)

As shown in the timeline(figure 3), both reactor types exhibit an increasing trend in time margin as break size increases. Larger breaks accelerate SG depletion but also enhance natural depressurization, reducing the reliance on operator-initiated bleeding. The analysis identifies critical threshold break sizes: for OPR-1000, breaks larger than 0.8 inches, and for APR-1400, breaks larger than 1.2 inches, naturally depressurize the RCS sufficiently to enable effective safety injection without additional operator intervention. These thresholds are crucial for emergency procedure development, as they define the conditions under which operator action is essential versus when passive system response suffices. Figure 6 compares the operator time margin (Δt) for initiating bleeding between OPR-1000 and APR-1400 across different break sizes, illustrating that OPR-1000 consistently provides a longer available response time and that the margin increases with break size up to the critical threshold for each reactor type.

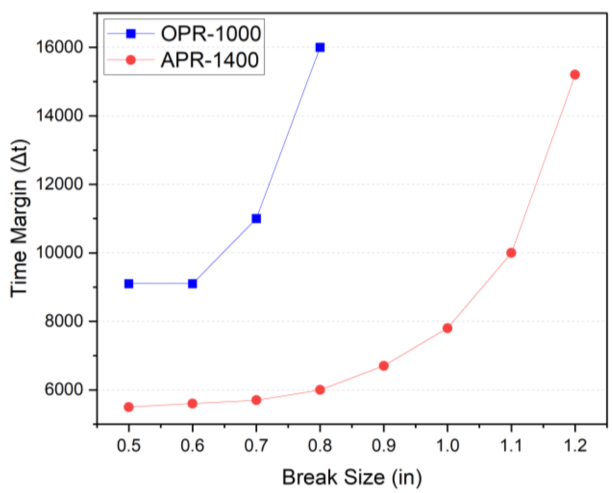

FIGURE 6. Time margin (Δt) as a function of break size for OPR-1000 and APR-1400

IV. Conclusion

This study demonstrates significant differences in operator time margins for safe Feed-and-Bleed (F&B) operation between OPR-1000 and APR-1400 under SBLOCA conditions. OPR-1000 provides a longer window for operator action (152–267 minutes) compared to APR-1400 (92–253 minutes) for the same break sizes, and for larger breaks, bleeding is not required due to sufficient natural depressurization.

These findings have direct implications for emergency operating procedures (EOPs) and operator training. For APR-1400, the shorter time margins necessitate stricter response protocols, faster decision-making, and potentially the integration of automated systems to reduce reliance on operator action. Conversely, OPR-1000 allows for more deliberate operator responses due to its longer margins. Training programs should be tailored accordingly, with APR-1400 operators focusing on rapid recognition and response, and OPR-1000 operators benefiting from more comprehensive scenario analysis.

Furthermore, the identified time margins support risk-informed safety assessments and EOP optimization. Future research should validate these results through full-scope simulator studies with actual operators, and examine the impact of different initial plant conditions and equipment availability on time margins. The development of advanced decision support tools, accounting for reactor-specific constraints, will further enhance operator performance and overall plant safety during SBLOCA events.

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