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

Time Margin Analysis of Feed-and-Bleed Operation in OPR-1000 and APR-1400 Using MARS Code

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

1. Introduction

Small Break Loss of Coolant Accident (SLOCA) in nuclear power plants occurs due to a break in the Reactor Coolant System (RCS). If not properly managed, this can lead to core damage. In such scenarios, if the secondary system, particularly the Auxiliary Feedwater System (AFW), fails to function properly, the Feed & Bleed (F&B) operation required. This operation involves depressurizing the reactor vessel and injecting cooling water through the Emergency Core Cooling System (ECCS) to ensure core cooling [1].

F&B is a cooling strategy used when normal heat removal pathways fail. It involves opening primary safety valves (SDS Valve in OPR-1000, POSRV in APR-1400) to release steam and depressurize the reactor, allowing ECCS to inject coolant effectively. When the primary system pressure decreases sufficiently, safety injection (SI) is activated to sustain core cooling. This method ensures the removal of decay heat from the reactor core and prevents excessive temperature rise.

The successful status of F&B operation heavily depends on operator decision-making and response time. In other words, operator intervention plays a critical role in F&B operation. When the Steam Generator (SG) Wide Range (WR) level drops below a certain threshold, operators must manually open the primary system safety valves to release steam [2]. Delays or improper actions can degrade cooling performance and accelerate accident progression, increasing the probability of core damage. The key challenge is to determine the optimal timing for bleeding initiation, as delayed action can negatively impact cooling performance. Given the differences in safety valve operation between OPR-1000 [3] and APR-1400, understanding these dynamics is essential for optimizing emergency response strategies.

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

1. The timing at which operators open the valves upon receiving the F&B signal when the SG WR level falls below 2%
2. The effect of operator intervention delays on cooling performance and core integrity.

The results of this study are expected to contribute to the improvement of Emergency Operating Procedures (EOP) and enhance operator training programs for each reactor type.

2. Methodology

This study is conducted using each reactor type's EOP and accident progression analysis reports[2]. By utilizing these resources, a comprehensive assessment of the F&B operation under SLOCA conditions is performed. The accident scenario follows the sequence : Reactor Trip, Safety Injection, AFW failure, RCS Bleeding.

The following are the event trees for OPR-1000 and APR-1400. 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 APR-1400 scenario, after RT, safety injection is successfully initiated. Subsequently, AFW fails, the Main Steam Safety Valve (MSSV) successfully opens, but ultimately, the secondary heat removal fails.

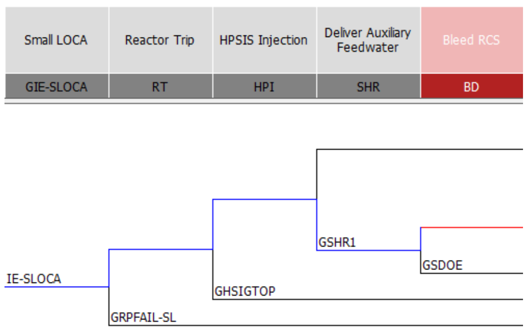

Fig. 1. Event tree of SLOCA scenario, OPR-1000

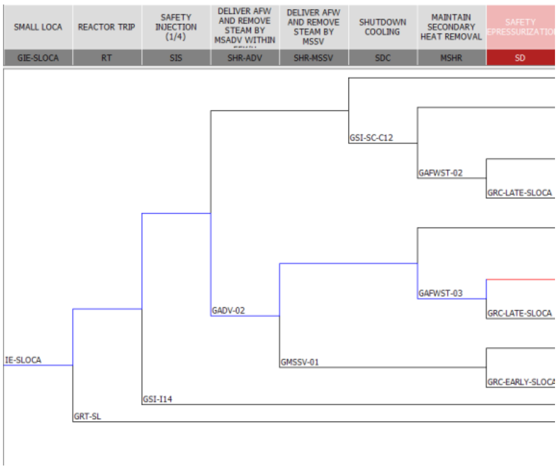

Fig. 2. Event tree of SLOCA scenario, APR-1400

2.1 Simulation Setup and Scenarios

F&B operation is expected to exhibit different behaviors depending on the break size during a SLOCA event. Therefore, simulations are conducted for break sizes of 0.5 in, 1.0 in, 1.5 in, and 2.0 in. According to the EOP, AFW injection is initiated when SG WR Level reaches 23.1%, and the bleeding decision is made when SG WR Level falls below 2%. Therefore, monitoring SG WR Level is crucial in determining the appropriate moment for operator action. The timing of valve opening is determined based on these signals.

2.2 Sensitivity Analysis of Operation Intervention Delay

During a SLOCA event, operators manually open the primary system depressurization valve upon receiving a signal. However, the response time can vary depending in the situation.

This study evaluates how delayed operator response affects core cooling efficiency, overall reactor pressure, and accident progression. Through sensitivity analysis, the maximum allowable time margin before core damage occurs is determined. Identifying this time margin is a critical aspect of this research, as it enables the determination of the optimal intervention timing to prevent core damage.

2.3 Key Signals and Operator Actions

During a SLOCA event, several key signals dictate operator response and accident management. These signals provide crucial information for initiating reactor protection systems and executing F&B operations :

- Reactor Trip Signal : Triggered by low pressurizer pressure (121.1MPa) or a drop in the Departure from Nucleate Boiling Ratio (DNBR). Reactor automatically shuts down the reactor to prevent further escalation of the accident.
- Safety Injection Signal : Following a reactor trip, reactor coolant pressure continues to decrease. When the system detects low-pressure conditions, it initiates the Emergency Core Cooling System (ECCS) to ensure cooling water injection into the core
- SG WR Level < 2% Signal : When the SG water level falls below 2%, it indicates a significant reduction in available secondary-side cooling. Operators must respond by opening the SDS Valve (OPR-1000) or POSRV (APR-1400) to depressurize the primary system and allow effective coolant injection.

Operator response to these signals is crucial in ensuring effective cooling and mitigating accident progression. Failure to respond promptly may lead to increased reactor pressure, reduced ECCS effectiveness, and heightened risk of core damage.

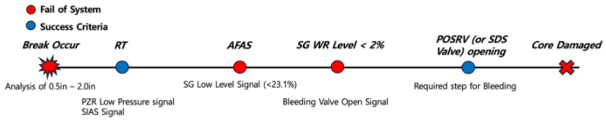

Fig.3 Time Table for F&B operation in SLOCA

3. Results and Discussion

3.1 Time Margin Analysis

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

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.

Table I: Time Margin Description of OPR-1000

OPR-1000	0.5in	1.0in
PZR Low Pressure Signal	1,412s (23m)	312s (5m)
SG Low Level Signal	4,780s (79m)	4,020s (67m)
SG WR Level 2%	5,858s (97m)	6,728s (112m)
Bleeding Point	13,148s (219m)	14,328s (241m)
Δ t (Time	7,300s (122m)	7,600s (128m)

Margin)		

Table II: Time Margin Description of APR-1400

APR-1400	0.5in	1.0in
PZR Low Pressure Signal	1,599s (27m)	355s (6m)
SG Low Level Signal	2,981s (50m)	2,191s (37m)
SG WR Level 2%	4,033s (67m)	3,697s (62m)
Bleeding Point	6,633s (111m)	6,297s (105m)
Δ t (Time Margin)	2,200s (37m)	2,600s (43m)

For OPR-1000, the maximum allowable time margins are 7,300 seconds for a 0.5in break and 7,600 seconds for a 1.0in break. In contrast, APR-1400 exhibits a significantly shorter allowable time margin, with 2,200 seconds for a 0.5in break and 2,600 seconds for a 1.0in break. These results indicate that APR-1400 requires a faster response time due to its faster SG depletion rate compared to OPR-1000. To further illustrate these findings, SG WR Level and PCT trend graphs are provided

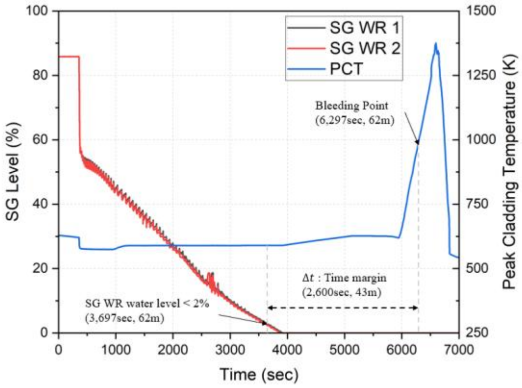

Fig. 4. 1.0in Break of APR-1400 in Time Margin 2,600s

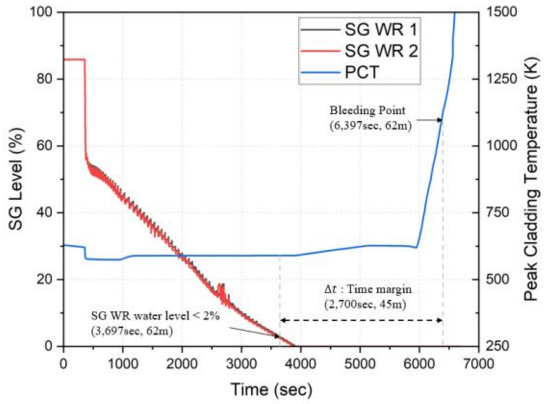

Fig. 5. 1.0in Break of APR-1400 in Time Margin 2,700s

3.2 Case of 1.5in and 2.0in Break

For 1.5in and 2.0in breaks, the analysis reveals that additional bleeding operations are not required. The break naturally functions as a pressure relief point, effectively reducing reactor vessel pressure and preventing core damage. Consequently, sensitivity analysis for delayed operator response is unnecessary in these cases. The results are further supported by graphical representations of reactor vessel pressure, SG WR Level, and PCT trends.

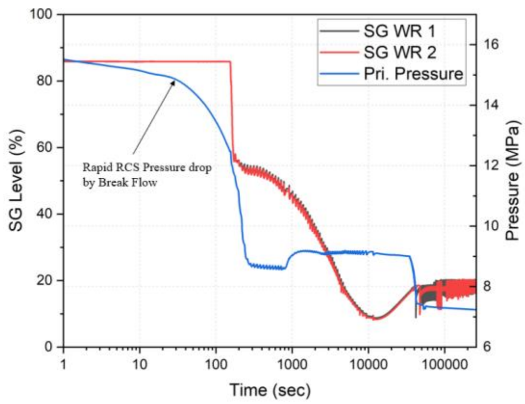

Fig.7. RCS Pressure drop in 1.5in Break of APR-1400

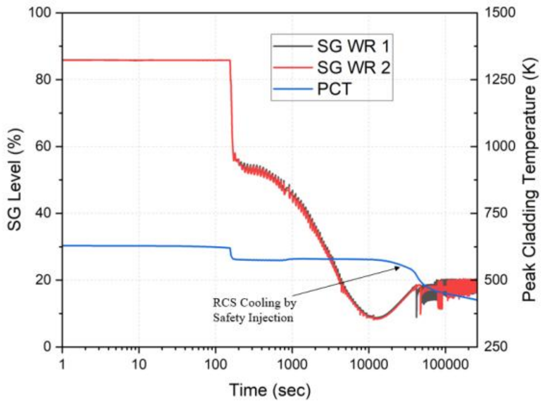

Fig. 6 Peak Cladding Temperature in 1.5in Break of APR-1400

4. Conclusion

The results indicate that APR-1400 has a shorter available time for operator intervention than OPR-1000. This highlights the necessity for stricter operational guidelines and faster decision-making processes in APR-1400 to prevent core damage. Additionally, the study underscores the importance of refining EOPs to incorporate optimized bleeding initiation timing. The findings can be used to improve EOP guidelines and enhance operator training, ensuring that operators are well-prepared to respond efficiently to SLOCA events in both reactor types.

Acknowledgements

This work was supported by the Nuclear Safety Research Program through the Regulatory Research Management Agency for SMRS (RMAS) and the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea (No. 1500-1501-409).

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