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Analysis of Recovery Time Margin of Auxiliary Feedwater Pump in OPR-1000 and APR-1400 Using the MARS-KS Code

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1. Introduction

A Small Break Loss-of-Coolant Accident (SLOCA) is an accident in which a break with a diameter of a few inches occurs in the Reactor Coolant System (RCS), causing a gradual loss of coolant inventory. Compared with a Large Break LOCA, the rate of pressure decrease is more gradual, and the primary system pressure is initially maintained. However, coolant inventory continues to deplete, leading to a potential degradation of core cooling performance. Therefore, it is essential to secure a secondary heat removal path through adequate auxiliary water supply[1].

In such situations, the Auxiliary Feedwater (AFW) system plays a critical role by supplying feedwater to the secondary side of the Steam Generator (SG), generating steam, and thereby removing the residual heat transferred from the primary side. In other words, decay heat produced in the reactor core is transferred to the SG through the reactor coolant, and the feedwater injected by the AFW absorbs this heat through evaporation and releases steam, establishing an effective heat removal path. Thus, during a SLOCA, the AFW serves as a decisive system in maintaining a vital safety function and preventing core damage, even in the absence of the Main Feedwater system[2].

If the AFW fails to inject, Feed and Bleed (F&B) operation, manually initiated by the operator, becomes necessary to ensure residual heat removal[3]. In this case, operators may hesitate to initiate F&B operation, because if a clear cue is not provided, its initiation entails the discharge of radioactive coolant into the containment structure[4]. So the timing of the operator's initiation of F&B is of great importance in preventing core damage[5].

In this context, a previous research by Kim[6] quantitatively analyzed the time margin for F&B initiation. By defining the point at which the SG level decreases to 2% as the reference, the study evaluated the available time margin for initiating F&B before core damage occurs, thereby providing a quantitative temporal criterion for the improvement of Emergency Operating Procedures (EOPs).

However, in actual operating conditions, there remains a possibility that the operator may succeed in restoring AFW injection while preparing for F&B. Therefore, if the operator can decide, based on the available time before core damage, whether to focus on AFW recovery or on preparing for F&B, accident management could be made safer and more reliable. Accordingly, it is necessary to establish a time criterion for evaluating the feasibility of securing an alternative heat removal path through AFW recovery.

2. Methodology

In this study, the recovery time margin of the Auxiliary Feedwater system during SLOCA was analyzed for OPR-1000 and APR-1400. The analysis was conducted using the MARS system thermal-hydraulic code.

2.1 Definition of Accident Scenario

This study followed the SLOCA scenario established in the previous research by Kim[6]: Reactor Trip – SI Success – AFW Failure. The following presents the event tree of SLOCA in OPR-1000 and APR-1400

The event trees for OPR-1000 and APR-1400 are illustrated as follows. In the case of OPR-1000, after Reactor Trip (RT), followed by the successful actuation of the High Pressure Safety Injection (HPSI). After this, the AFW injection fails, leading to the loss of the secondary cooling function. In the case of APR-1400, RT occurs and safety injection is also initiated as expected. Yet, with the subsequent failure of AFW, even though the Main Steam Safety Valve (MSSV) opens successfully, the reactor ultimately experiences a failure of secondary heat removal. Since both the OPR-1000 and APR-1400 follow the same sequence—where safety injection is successful, AFW initially fails leading to secondary cooling failure, and is later recovered—the little differences in the event tree are not expected to significantly affect the analysis results.

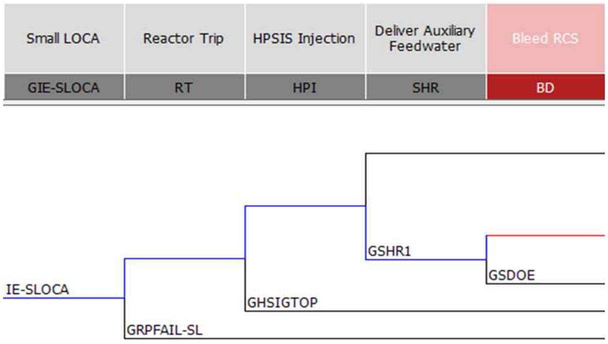

Fig. 1. Event tree of SLOCA scenario, OPR-1000

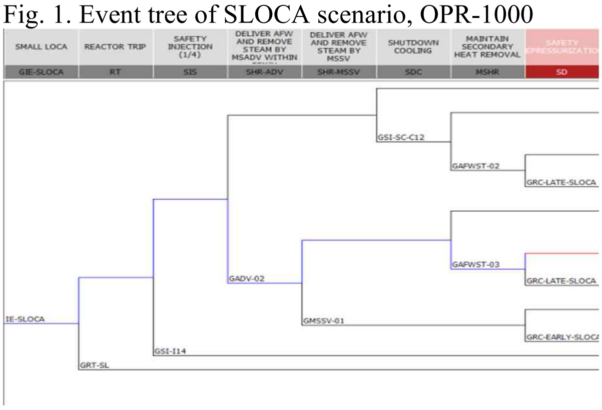

Fig. 2. Event tree of SLOCA scenario, APR-1400

The key difference compared with the previous study is that AFW is assumed to be recovered. While AFW is considered unavailable at the time of AFAS initiation, it is restored after a specified delay, and the AFW recovery time margin that prevents core damage (CD) is derived. In this scenario, AFW recovery is assumed to occur before the initiation of Feed and Bleed providing an alternative cooling path prior to entering F&B.

2.2 Analysis Method

First, the scenario was modeled under the assumption that both AFW and Feed and Bleed operation failed, and the time when the SG wide range level reached 23.5% as well as the time to core damage were identified. Then, after the SG WR level reached 23.5%, AFW was assumed to be recovered following a specified delay (e.g., 300s, 600s, 900s), and the AFW recovery time margin that prevents CD was derived.

The break size of the reactor coolant system was varied from 0.5 inch to 2 inches in order to evaluate the differences in SG depletion rate and core cooling behavior depending on the break size. Core damage was defined as the point at which the peak cladding temperature (PCT) reached 1477 K.

The recovery time margins of AFW derived from the analysis are compared with the Feed and Bleed operation time margins presented in a previous study. In that work, the time margin for initiating F&B was quantified by defining the point at which the SG WR level falls to 2% as the reference, and evaluating the allowable delay time before core damage. This provided a quantitative temporal criterion for improving Emergency Operating Procedures. The present study applies the same approach to AFW recovery, with the objective of establishing a quantitative basis to support operator decision-making in determining whether to focus on AFW recovery or on preparing for F&B operation during accident conditions.

3. Result and Discussion

AFW time margin is defined as the maximum allowable time between the SG WR level reaching 23.5% and the initiation of AFW injection, without leading to core damage. This margin indicates the maximum period during which the operator can successfully restore AFW before the accident develops into an unrecoverable condition.

Table 1: Time margin description of OPR-1000

OPR-1000	0.5in	0.6in	0.7in	0.8in
SG WR Level 23.5%	2,515s (42m)	2,194s (37m)	1,923s (32m)	1,760s (29m)
SG WR Level 2%	2,789s (46m)	2,399s (40m)	1,948s (32m)	1,782s (30m)
*Bleeding Time Margin	9,100s (152m)	9,100s (152m)	11,000s (183m)	16,000s (267m)
**AFW Time Margin	9,400s (157m)	9,400s (157m)	11,150s (186m)	16,200s (270m)

*Maximum allowable time between the SG WR level reaching 2% and the initiation of Bleeding
**Maximum allowable time between the SG WR level reaching 23.5% and the initiation of AFW injection

Table 2: Time margin description of APR-1400

APR-1400	0.5in	0.6in	0.7in	0.8in
SG WR Level 23.5%	6,511s (109m)	5,925s (99m)	5,470s (91m)	5,449s (91m)
SG WR Level 2%	7,429s (124m)	7,155s (119m)	6,852s (114m)	6,929s (115m)
Bleeding Time Margin	5,500s (92m)	5,600s (93m)	5,700s (95m)	6,000s (100m)
AFW Time Margin	6,500s (108m)	6,600s (110m)	6,800s (113m)	7,300s (122m)

APR-1400	0.9in	1.0in	1.1in	1.2in
SG WR Level 23.5%	5,618s (94m)	5,852s (98m)	6,120s (102m)	6,543s (109m)
SG WR Level 2%	7,149s (119m)	7,528s (125m)	1,949s (132m)	8,689s (145m)
Bleeding Time Margin	6,700s (112m)	7,800s (130m)	10,000s (167m)	15,200s (253m)
AFW Time Margin	8,300s (138m)	9,200s (153m)	11,500s (192m)	12,500s (208m)

For OPR-1000, the maximum AFW recovery time margins were 9,400 s, 9,400 s, 11,150 s, and 16,200 s for break sizes from 0.5 in to 0.8 in, respectively. For break sizes lager than 0.9 inches, the RCS pressure was maintained at a sufficiently low level through the break itself, allowing safety injection to be sustained effectively, and thus further analysis was not required.

For APR-1400, the maximum AFW recovery time margins were 6,500 s, 6,600 s, 6,800 s, and 7,300 s for break sizes from 0.5 in to 0.8 in, respectively. For break sizes from 0.9 in to 1.2 in, the corresponding values were 8,300 s, 9,200 s, 11,500 s, and 12,500 s. For break sizes of 1.3 in and larger, the RCS pressure remained low enough to allow stable safety injection, and therefore additional analysis was unnecessary.

These results demonstrate that, for the same break size, APR-1400 experiences faster depletion of SG water level and shorter AFW recovery time margins compared with OPR-1000, indicating the necessity of more rapid recovery actions in APR-1400.

In addition, for both OPR-1000 and APR-1400, the depletion time of the SG WR level from 23.5% to 2% was found to be nearly equal to the difference between the bleeding time margin and the AFW recovery time margin, suggesting that the initiation times of bleeding and AFW recovery are essentially similar. This implies that, although the mechanisms differ, AFW providing feedwater injection and F&B relying on depressurization, the fundamental principle of securing a heat removal pathway through the steam generators remains the same. Consequently, from the perspective of Emergency Operating Procedures, operators should pursue AFW recovery and prepare for F&B operation in parallel within these time margins.

4. Conclusion

These results indicate that, from the perspective of AFW recovery, APR-1400 provides a shorter response time compared with OPR-1000, thereby requiring more rapid operator's action.

Furthermore, it was confirmed that the two time margins identified during a SLOCA—the initiation of AFW recovery and the initiation of F&B operation—exist within a similar range. This suggests that, rather than treating these actions as independent alternatives, operators should pursue AFW recovery and prepare for F&B operation in parallel within the limited time following the AFAS signal, in order to effectively prevent progression to core damage. This findings are expected to contribute to the improvement of EOPs and the reinforcement of operator training. In addition, from a Probabilistic Safety Assessment perspective, the results may be utilized to refine SLOCA accident scenarios and to improve event tree modeling.

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