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Assessment of the Emergency Operating Procedures for Main Steam Line Break Accident of the OPR1000 Nuclear Reactor using the MARS code

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1. Introduction

As a part of nuclear power plant safety assessment, Probabilistic Safety Assessment (PSA) [1] is required. In this study, we conducted simulation and evaluation of one of the accident scenarios defined in PSA, the Main Steam Line Break (MSLB) [2,3] accident, using the optimal thermal-hydraulic analysis code MARS. We have simulated the Final Safety Analysis Report (FSAR)'s [4] scenario in which EOP [5] measures are not taken and the scenario in which EOP measures are taken in Uljin units 3 and 4, OPR1000 plant. We have compared the major thermal-hydraulic variable results of two scenarios. Through comparing the results, we confirmed that the EOP measures contribute to maintenance integrity of the plant by achieving the early entry condition for the Shutdown Cooling System (SCS) [6].

EOP procedures have been developed, and their validity is assessed using nuclear system design codes. However, these codes may have discrepancies from actual phenomena due to conservative assumptions. Hence, in this study, we simulated MSLB accidents and EOP actions using the MARS [7] code, an optimal thermal-hydraulic analysis code. The MARS code, developed by the Korea Atomic Energy Research Institute (KAERI), has been used for nuclear power plant design and accident analysis for over 30 years. It incorporates 1D and 3D thermal-hydraulic analysis modules, accurately simulating single-phase and two-phase flow behavior in normal and transient states. The reliability of calculation results is high due to extensive verification and widespread use in accident analysis.

For this study, the existing MARS input model for Uljin Units 3 and 4 (OPR1000 nuclear power plants) [8] was used to simulate MSLB accidents. We simulated the scenario with MSLB without operator actions specified in FSAR, and then calculated the scenario with EOP actions. By comparing the results of these two scenarios, we confirmed that EOP actions contribute to early achievement of the ultimate goal—securing entry conditions for the SCS after an MSLB accident. Additionally, EOP actions minimize steam leakage until entry condition satisfaction, prevent core re-criticality, and ensure continuous core cooling and plant integrity maintenance.

2. Input model of MARS code for simulating EOP actions in MSLB accident

The MARS code has been utilized in assessing and interpreting EOP actions in different power plants [9]. In this study, we utilized the input data from the report on the development of the MARS code input model for the operational analysis of Units 3 and 4 at the Uljin nuclear power plant [8] as the fundamental input for our analysis. The MARS input model was updated to simulate the MSLB accident and include components and control logic for EOP operator actions. The operator's EOP measures are arranged in the order of incident occurrence in Table I.

Table I: EOP measures of the MSLB accident

steps	EOP measures
1	Confirmation of reactor trip due to variable overpower and turbine trip, MFW trip
2	Adjusting intact-side SG's water level with MD/TD-AFW injection
3	HPSI inject due to SIAS and flow rate adjustment based on HPSI termination conditions
4	Confirming and implementing the trip of one RCP per loop along with HPSI inject
5	Locking of MSIV due to MSIS
6	Opening of ADV on the intact steam line side and adjusting the opening of ADV based on RCS temperature and cooling rate
7	Adjusting PZR water level through PSS
8	Initiating operation based on satisfying the entry conditions for the SCS

2.1 Modification of the main steam line model

The steam line between the SG outlet and the Main Steam Line Isolation Valve (MSIV) was originally simulated with 3 grids, but it has been expanded to 4 grids to model a MSLB accident on both ends. A rupture valve has been placed in the middle to facilitate the simulation of the MSLB scenario.

2.2 Atmospheric Dump Valve (ADV) model

The Atmospheric Dump Valve (ADV) is the most critical valve used for the cooling of the reactor by operators following EOP actions after an MSLB accident. Since the ADV is only opened when operator actions are taken, input data regarding control logic [10] is needed to account for operator actions.

After the MSLB accident, operators do not fully open all ADVs; instead, they partially open them and adjust the valve openings based on the temperature of the RCS. Additionally, operator actions are simulated using the logical trip cards in the MARS code to maintain the RCS cooling rate between 45 ℃/hr and 35 ℃/hr

3. Assessment of the validity of EOP actions in MSLB accident using the MARS code

The initial steady-state conditions were calculated using the design values provided in the report on the development of the MARS code input model for operational analysis of Uljin Units 3 and 4 [7] (Table II)

Table II: Initial steady-state conditions

Parameter	Design	MARS value
Reactor power, MWt	2815.0	2815.0
Out-core temperature, K	600.48	601.26
In-core temperature, K	569.89	569.35
Coolant flow rate, kg/s	14,944.8	14,961.0
PZR pressure, MPa	15.51	15.516
PZR water level, %	52.6	52.48
SG pressure, MPa	7.38	7.38
SG NR water level, %	44.0	44.0

3.1 Results of MSLB scenario without EOP actions specified in FSAR

After the occurrence of MSLB accident, excessive steam leakage occurs through the ruptured section, leading to a decrease in pressure and temperature in the ruptured-side SG (SG-A). Consequently, the primary cooling system is rapid cooled due to the heat transfer effect of the coolant temperature, ultimately resulting in a positive reactivity. This leads to an increase in reactor power, triggering a reactor trip signal at 7.05 seconds. After reactor trip, core power, PZR pressure, and water level decrease. The intact-side SG (SG-B)'s pressure, temperature, and water level are decreased as well.

At 26.1 seconds after the accident, the pressure of the SG-A drops to 5.43 MPa, triggering the Main Steam Line Isolation Signal (MSIS). Consequently, at 28 seconds, the Main Feedwater Isolation Valve (MFIV) closes completely due to MSIS, and at 119.3 seconds, the MSIV locks completely. The PZR pressure drops to 10.72 MPa at 53.2 seconds, leading to the initiation of the Safety Injection Actuation Signal (SIAS). The PZR water level falls below the measurement range at 64 seconds, and High Pressure Safety Injection (HPSI) is injected at 83.2 seconds, 30 seconds after the occurrence of the SIAS. The introduction of HPSI leads to an increase in PZR's pressure, water level, and the pressure of the SG-B. The oscillation of PZR's pressure and hot-leg's temperature occurs because, in the FSAR scenario, auxiliary feedwater (AFW) is injected into the SG-A. This leads to rapid and repetitive heat transfer between the primary and secondary systems. The behavior of reactor system's pressure and hot leg's temperature is represented in Figure. 1. and Figure. 2., respectively.

From the MARS code calculation results, it is observed that in the scenario which EOP actions are not taken as in the FSAR, effective cooling of RCS does not occur after HPSI injection. The RCS temperature decreases very slowly even after 5,000 seconds. In the FSAR scenario, if operator cooling actions were initiated, the injection of AFW into the SG-A would stop. However, in this scenario without operator actions, the injection of AFW continues, resulting in ongoing steam leakage through the ruptured steam line. Figure. 3. illustrates the continuous increase in accumulated mass of steam leakage through the ruptured steam line. In conclusion, to minimize the potential for external release of radioactive materials through the ruptured section, ensure stable cooling of the primary cooling system, and swiftly secure the entry conditions for the SCS, appropriate EOP actions by operators are crucial.

3.2 Results of MSLB scenario with EOP actions

Due to the MSLB accident, the core power output increases to about 2,913.5 MW, approximately 103.5% of the initial output. About 7 seconds after the accident, reactor and turbine trips occur, and both MFW injections stop. Following the accident, the ruptured side SG-A's water level drops sharply and PZR and the intact-side SG-B water levels also decrease due to reactor trip and MFW injection trip. At around 2 seconds after reactor trip, AFW injection restores SG-B water level.

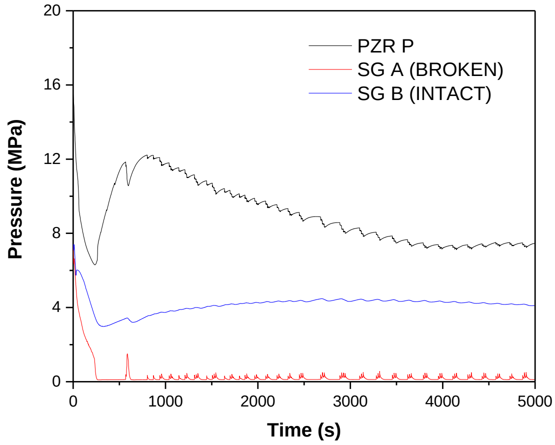

Fig. 1. Pressure of the reactor system

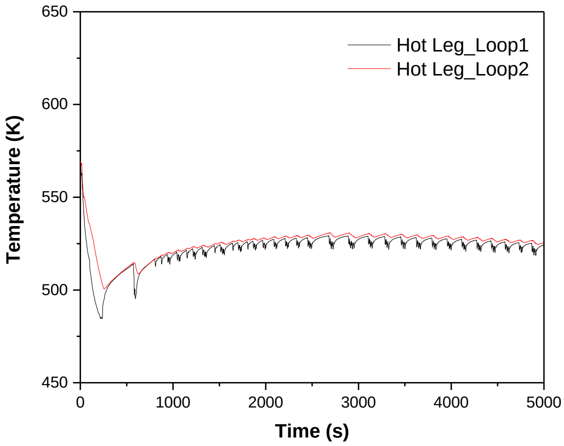

Fig. 2. Temperature of RCS (Hot Leg)

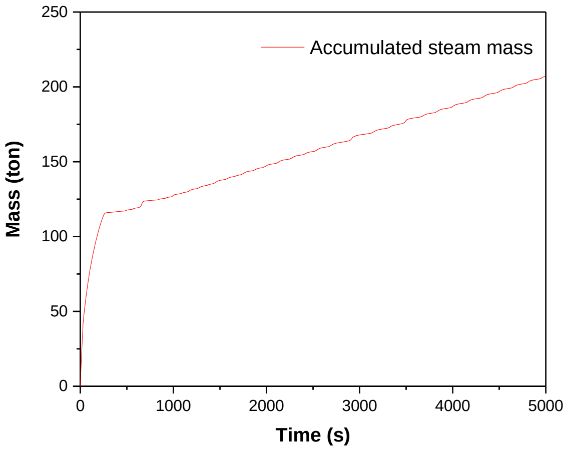

Fig. 3. Accumulated mass of the released steam

Figure. 4. illustrates the changes in reactor system's pressure. Following the accident, at around 31.3 seconds, the SIAS is initiated due to excessive cooling of the RCS by reactor trip. At 61.3 seconds, HPSI is injected, causing an increase in PZR and the SG-B pressures. Operator actions control HPSI flow based on RCS pressure and EOP criteria. The termination criteria for HPSI are as follows: RCS subcooling greater than 15°C, PZR level exceeding 33%, at least one SG water level maintained or restored between 23% and 90%, allowing or restoring primary system heat removal, or if the reactor upper head level is above 16%. Concurrently, one RCP per loop is tripped. The SG-A pressure decreases significantly due to steam leakage. At 63.09 seconds, SG-A pressure reaches the MSIS trip setpoint of 6.125 MPa, leading to the closure of the MSIV starting at 68.09 seconds and SG-A is effectively isolate. The pressure in SG-A equals to atmospheric pressure around 684 seconds.

After reactor trip, at 1,807 seconds, the ADV on the SG-B side open, leading to reductions in PZR and SG-B pressures, water level along with RCS temperature. The SG-B ADV flow is represented in Figure. 5. Afterwards, the water level of the PZR is maintained between 33% and 70% by the operating action of the HPSI and PSS, and the water level of the SG-B is maintained between 70% and 90% by adjusting the flow rate of the AFW. The reason why the pressure of the PZR and SG-B vibration is because of the ADV opening adjustment according to the cooling rate between 35 ℃/hr and 45 ℃/hr of the hot leg and the operation of HPSI and PSS according to the water level of the PZR.

High-temperature RCS cooling behavior is represented in Figure. 6, showing differences from the FSAR scenario (Figure. 4.). After the MSLB accident, RCS cools to the ultimate SCS entry temperature of 449.58 K at around 23,890 seconds. The cumulative steam leakage through the ruptured steam line is shown in Figure. 7. While the cumulative leakage steadily increases in the FSAR scenario, it remains stable at 100.2 tons from 870 seconds onward in the scenario with EOP actions, indicating that steam leakage is effectively mitigated.

The MARS code simulations demonstrate that implementing EOP actions minimizes steam leakage, ensures early achievement of SCS entry temperature, maintains stability and safety of various systems, and contributes to core stability post-accident.

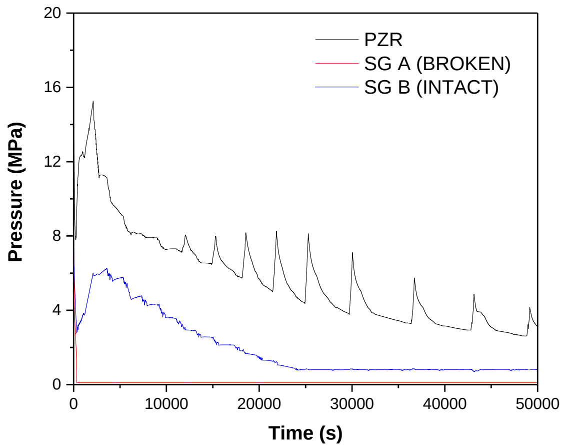

Fig. 4. Pressure of the reactor system

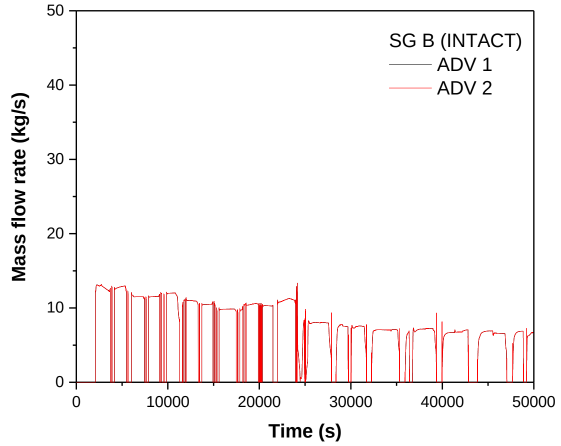

Fig. 5. Mass flow rate of ADV (intact-side steam line)

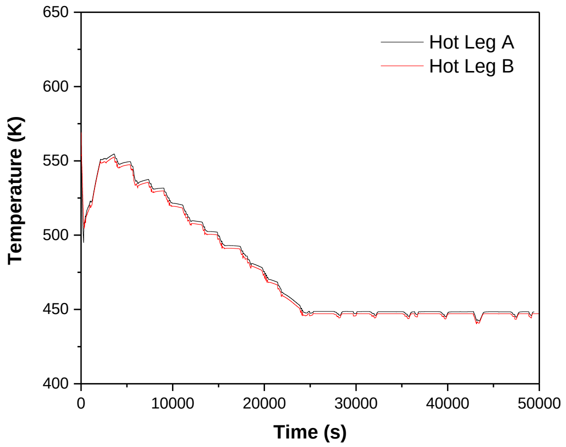

Fig. 6. Temperature of RCS (Hot Leg)

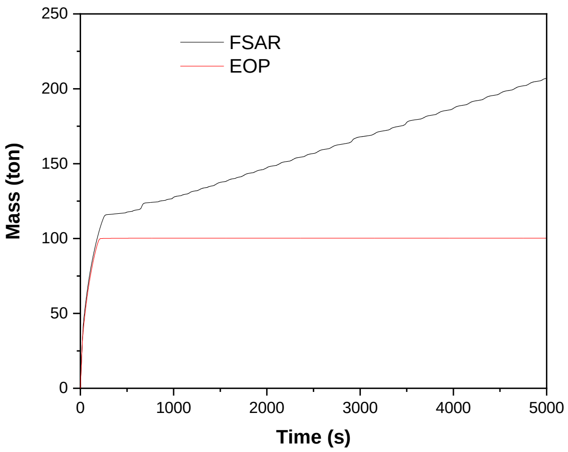

Fig. 7. Accumulated mass of the released steam

4. Conclusions

In this study, the validity of EOP for MSLB accidents in Uljin Units 3 and 4 reactors was evaluated using the MARS code. For this evaluation, safety functions to maintain the integrity of the reactor core after an MSLB event were identified, and EOP actions to preserve these safety functions were defined as the event sequence. The existing MARS input data for Uljin Units 3 and 4 were modified to include the MSLB accident and corresponding EOP actions. Furthermore, simulations were conducted for both the EOP-applied scenario and an FSAR scenario where EOP actions were not taken. The results from these two scenarios were then compared.

In the scenario where EOP actions were properly executed, measures such as opening and controlling the MSIVs and ADV, regulating the HPSI injection mass flow rate based on termination criteria, operating the PSS, and controlling the AFW flow to the intact-side SG were taken appropriately. As a result, efficient cooling of the RCS was achieved, and the final cooldown condition for the SCS at 449.58 K was achieved ahead of schedule, by 23,890 seconds after the accident. By comparing the results of the two scenarios, it was confirmed that EOP actions contribute to the early achievement of the cooldown conditions and stable cooling of the reactor coolant system to the desired temperature. Additionally, they minimize the possibility of steam release and the associated radioactive material release. In conclusion, the EOP measures following an MSLB accident were found to be valid from the perspective of enhancing the safety of the nuclear power plant.

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