Optimization of EDV and ERV Design Ranges for SMR LOCA Mitigation using MARS-KS Code

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1. Introduction

The development of small modular reactors (SMRs) in Korea has transitioned toward an all-passive safety architecture to ensure robust accident tolerance without the need for external power or operator intervention [1]. These safety functions are primarily managed by integrated passive systems, including the Passive Auxiliary Feedwater System (PAFS), the Passive Containment Cooling System (PCCS), and the Passive Emergency Core Cooling System (PECCS). Among these, the PECCS is a critical innovation designed for Loss-of-Coolant Accident (LOCA) mitigation, utilizing the Emergency Depressurization Valve (EDV) and Emergency Relief Valve (ERV) to manage reactor pressure and coolant inventory. However, given the novel design of the PECCS, there is limited empirical data regarding the complex thermal-hydraulic interactions between these valves during transient events. Since the system's efficacy is highly sensitive to specific valve design parameters, a comprehensive analysis is required to establish a quantitative technical basis for SMR safety certification.

2. Methodology and results

2.1 Development of SMR MARS-KS input model

The SMR plant configuration for this numerical analysis was implemented using the MARS-KS code [2], with the nodalization shown in Fig. 1.

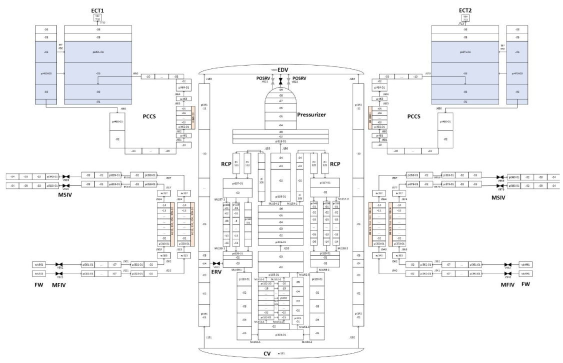

Fig. 1 Nodalizaiton of the SMR for MARS-KS input model

The model integrates the primary and secondary circuits with passive safety systems, specifically the PCCS and PECCS. The primary system features an integral reactor design where core-heated coolant circulates through the upper guide structure (UGS) and downcomer , driven by four RCPs while pressure is regulated by a top-mounted pressurizer and POSRVs. To facilitate heat removal, the secondary system employs four independent steam and feedwater lines that form an isolated closed loop via MSIV and MFIV closure upon reactor trip.

For long-term accident mitigation, the PCCS utilizes heat exchangers in the upper containment connected to external Emergency Cooling Tanks (ECTs) , absorbing thermal energy to stabilize containment pressure through natural circulation. Concurrently, the PECCS, comprising the EDV and ERV, manages reactor inventory : the EDV rapidly depressurizes the RV by discharging steam , while the ERV establishes a recirculation path for accumulated coolant in the CV to return to the RV. Both valves are designed to actuate automatically upon a low pressurizer water level signal.

2.2 Definition of the analyzed accident

To assess the operational efficacy of the PECCS, a Loss-of-Coolant Accident (LOCA) involving a Modular Make-up and Purification System (MMPS) pipe rupture was analyzed as the representative transient. [3] As depicted in Fig. 2, two potential break locations were identified based on the MMPS configuration: the letdown line in the upper reactor vessel (RV) and the charging line in the lower RV region.

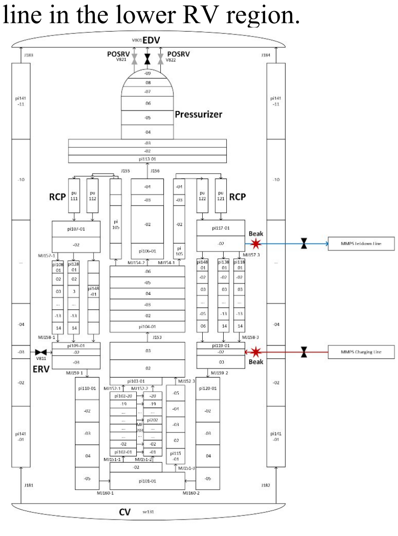

Fig. 2 LOCA scenarios considered in this study according to

the break location in the MMPS line.

The primary safety objective during a LOCA is the prevention of core uncovery to preclude subsequent core damage. Between the two scenarios, a rupture in the charging line results in a more rapid depletion of reactor coolant due to its lower elevation, leading to earlier core exposure compared to a letdown line break. Given this heightened temporal severity, the charging line break was established as the limiting, conservative bounding case for the safety evaluations in this study.

2.3 Thermal-Hydraulic Analysis under LOCA Scenarios using MARS-KS

To collect a comprehensive dataset for the safety assessment of the SMR, numerical simulations were performed using the MARS-KS code based on the limiting charging line break LOCA scenario. The investigation utilized the MARS-KS code to quantitatively analyze the influence of four primary variables: the break area, the flow areas of the EDV and ERV, and the valve actuation delay times. The break area was adjusted between 0.5 and 2.0 inches in 0.5-inch increments, specifically reflecting the MMPS piping diameter of 2 inches. For the passive safety valves, the flow areas of the EDV and ERV were evaluated from a minimum of 0.5 inches up to a maximum of 6.0 inches in 1.0-inch increments. Furthermore, the valve opening delay times were analyzed at 10-minute intervals, ranging from immediate opening to 40 minutes. This structured approach using MARS-KS resulted in a total of 980 simulation cases, providing the necessary resolution to capture the complex thermal-hydraulic performance and accident mitigation boundaries of the SMR.

2.4 Results

A total of 980 thermal-hydraulic simulation cases were analyzed to identify feasible design combinations for the passive safety valves. For each combination of EDV, ERV, and open delay time, the minimum RV water level and the maximum CV pressure were evaluated over all break areas. Design combinations were first screened based on the core cooling criterion. Only cases that maintained the minimum RV water level above core height across all break conditions were considered, ensuring complete prevention of core uncovery. For the remaining feasible cases, the containment response was quantified by defining the maximum CV pressure for each design combination as the highest value observed among all break scenarios. A conservative selection criterion was then applied by introducing a pressure margin of 0.5 MPa above the minimum value of these maximum pressures. It should be noted that this margin was instead introduced as an assumed conservative allowance for comparative design evaluation.

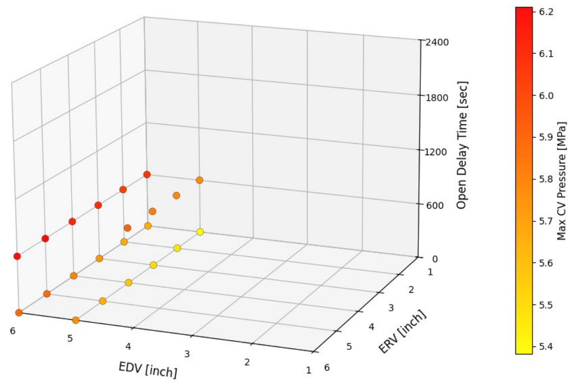

Fig. 3 Design space of feasible valve configurations satisfying the no-core-uncovery criterion (color indicates maximum containment pressure).

Figure 3 presents the resulting design space, where each point represents a feasible design combination satisfying the no-core-uncovery condition. The results in Fig. 3 represent aggregated thermal-hydraulic responses over all break scenarios, providing a comprehensive basis for evaluating the design feasibility. The color scale indicates the maximum containment pressure corresponding to each design, defined as the worst-case value among all break areas. Within this constrained design space, a conservative and practical design envelope was identified as:

EDV diameter: 5 inch
ERV diameter: 1–3 inch
Open delay time: 0–600 sec

All combinations within this envelope satisfy both the core cooling requirement and the containment pressure criterion defined in this study. These results provide a consistent basis for selecting robust design parameters for passive safety systems, while allowing flexibility for further refinement in detailed SMR design.

3. Conclusions

This study evaluated the design space of passive safety valves for an i-SMR system based on MARS thermal-hydraulic simulations under LOCA conditions. A conservative safety criterion was applied by preventing core uncovery and limiting containment pressure with an assumed margin of 0.5 MPa. Based on this analysis, a feasible design range was identified as EDV 5 inch, ERV 1–3 inch, and actuation delay time of 0–600 sec. All combinations within this range were found to satisfy both core cooling and containment pressure requirements. These results provide a practical basis for selecting robust design parameters for passive safety systems and can support future SMR design and operational strategies.

ACKNOWLEDGEMENT

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