

## Probabilistic Safety Assessment of Series-Configured Redundant ECCS Malfunction-Prevention Valves in a Water-Cooled SMR

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### 1. Introduction

In NuScale's small modular reactor (SMR), the emergency core cooling system (ECCS) provides core cooling by recirculating primary-side coolant through the opening of the ECCS valves [1]. In this design, unintended opening of the ECCS valve can decrease the primary-side coolant inventory and compromise reactor safety. To prevent this, NuScale installed an inadvertent actuation block (IAB) valve, which has a malfunction-prevention (MP) function, in the ECCS valve. The IAB valve should satisfy the single-failure criterion by redundancy because it is classified as safety-related component [2]. However, the NRC Commission voted not to apply the single-failure criterion to the IAB valve's MP function during the standard design approval review of the NuScale US600 [3]. The single-failure criterion is an important safety requirement that implements defense-in-depth by requiring redundancy to enhance the reliability of reactor safety systems [4]. From this perspective, the NRC Commission's decision not to apply the single-failure criterion to the MP function of the IAB valve may be considered an unusual regulatory judgment, particularly because the IAB valve is a first-of-a-kind design and its reliability has not been demonstrated by sufficient operational experience. However, the publicly disclosed basis for this decision is limited to general statements that, consistent with established risk-informed decision-making practices, even if the IAB valve's MP function were to fail, the Commission's safety goals would still be satisfied. Accordingly, no publicly available quantitative evaluation of its impact on reactor safety has been identified. Therefore, it is necessary to quantitatively examine the safety implication that could have been obtained by the NRC's risk-informed decision-making.

The objective of this study is to assess the impact of applying the single-failure criterion to the MP function of valves with features similar to those of IAB valves on reactor safety. The variation in reactor safety with the number of installed MP valves was examined.

### 2. Principles of ECCS valve operation including malfunction-prevention valve

As shown in Fig. 1, some SMRs (e.g., US600, US460, and i-SMR) that adopt a ECCS design utilizing primary coolant recirculation to mitigate accidents consist of a

ECCS configured with only valves [1, 5, 6]. This design enables core cooling using only the valves installed at the top of the reactor vessel (RV) and those installed on the side of the RV. The coolant vaporized in the core is discharged from the RV to the containment vessel (CV) through the valves located at the top of the RV, condenses along the containment wall, and then returns to the RV through the side valves.

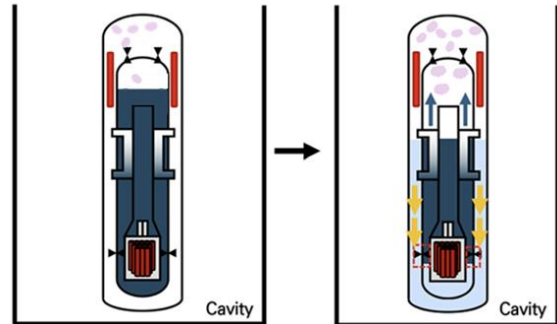


Fig. 1. SMR with a recirculation-type ECCS [7]

Each ECCS valve may consist of four components as shown in Fig. 2: a main valve, a MP valve, a reset valve, and a trip valve. The MP valve is positioned between the trip valve and the main valve pathway. The MP valve prevents unintended opening of the main valve. Under normal operating conditions, the MP valve remains open. However, when the trip valve is actuated, the MP valve closes. This closed state is maintained until the RV–CV differential pressure drops to the critical threshold, thereby preventing the main valve from unintended opening. When differential pressure is below the threshold, the MP valve reopens, thereby permitting the main valve to open. Therefore, if the single-failure criterion is applied to the valve closure function serving as the MP function shown in Fig. 2, series redundancy of the MP valve is required, as shown in Fig. 3.

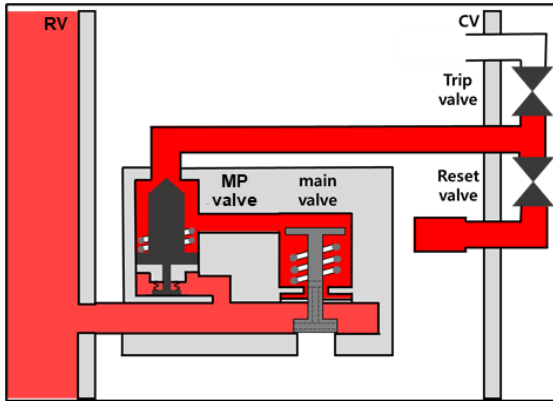


Fig. 2. Schematic of ECCS valve at normal operating conditions

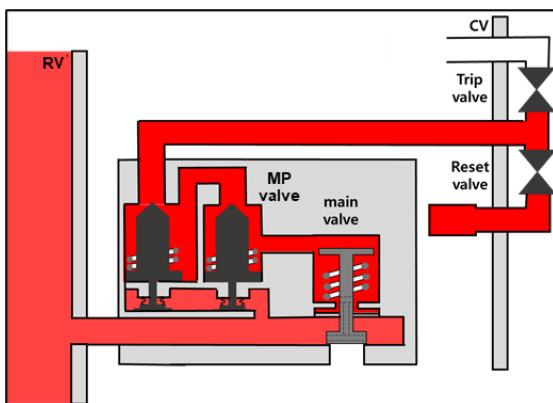


Fig. 3. Schematic of the ECCS valve including series redundancy of the MP valves under normal operating conditions.

### 3. Development of a Safety Assessment Model

This study was performed using a PSA model of a water-cooled SMR similar to the US460 and prototype i-SMR designs proposed in previous studies. [8, 9]. However, the i-SMR is currently under detailed design, and its current configuration differs from that assumed in this study.

For the target SMR ECCS, it was assumed that a valve on the top part of the RV and a side valve are sufficient to mitigate design-basis accidents. However, to satisfy the single-failure criterion for a ECCS valve to open, one additional valve was installed at each location, resulting in an ECCS configured with two top valves and two side valves [8,9].

#### 3.1 Scenarios for MP Function Actuation

To incorporate the MP function of the valves, the FT for the target SMR was modified as follows. The primary scenarios in which the MP valves should prevent the inadvertent opening of the ECCS include: (1) loss of direct current (DC) power, (2) inadvertent operation of the top ECCS trip valve, and (3) inadvertent operation of the side ECCS trip valve. The closure function of the MP valve was incorporated into the event tree (ET) heading to account for prevention of main valve opening

following a loss of DC power to the trip valve or inadvertent actuation of the top or side ECCS trip valve.

#### 3.2 Fault Tree of MP valve

In this study, the MP valve was modeled separately to distinguish between its closure function, designed to prevent inadvertent ECCS opening, and its opening function, required for intended ECCS operation.

Fig. 4 shows a typical fault tree (FT) for an top ECCS valve configured with a MP valve.

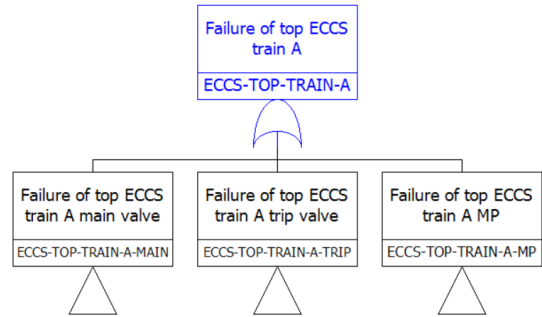


Fig. 4. FT for an top ECCS valve configured with a MP valve

Figure 5 shows the FT for the opening function of a top ECCS MP valve.

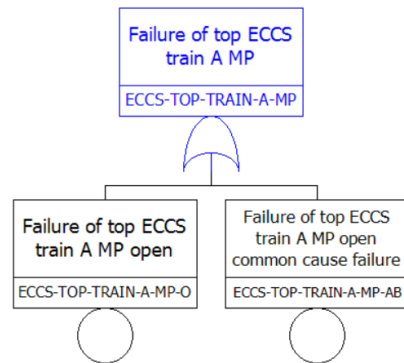


Fig. 5 FT for the opening function of a top ECCS MP valve

Fig. 6 shows the FTs for the closure function of the MP valve, which is intended to preclude loss of DC power and inadvertent operation of an ECCS trip valve. Left is about a top ECCS MP valve, right is about a side ECCS MP valve.

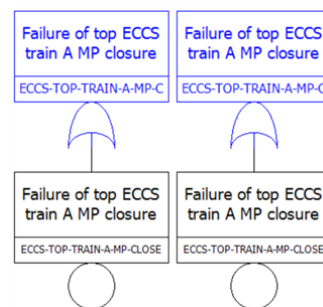


Fig. 6 FT for the close function of ECCS MP valves

#### 4. Sensitivity of Core Damage Frequency to the Number of MP Valves

The Core Damage Frequency (CDF) according to the MP valve configuration was evaluated by incorporating the considerations discussed in the above section into the SMR PSA models of the previous studies [8,9]. Fig. 7 presents the normalized CDF values according to the number of MP valves. The CDF values for the cases with zero, one, and two MP valves were normalized by dividing each CDF value by the CDF for the one MP valve case. The cases are ranked in descending order of CDF as follows: zero MP valve, two MP valves, and one MP valve.

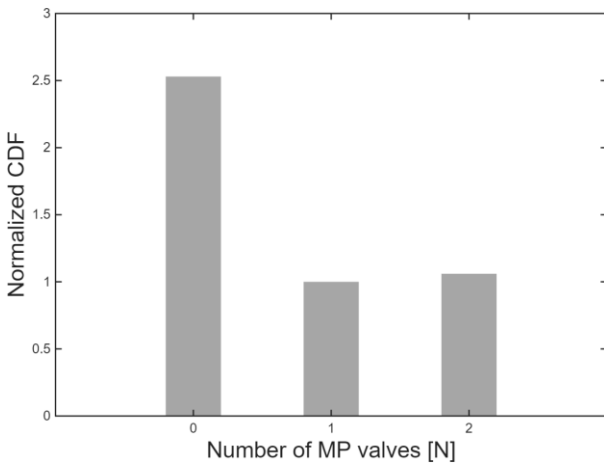


Fig. 7 Normalized CDF to the Number of MP Valves

To examine why increasing the number of MP valves to implement the MP function did not lead to a reduction in CDF, the scenarios were classified according to whether the MP function was involved.

- Group A:
  - Scenarios associated with the loss of DC power initiating event
  - Scenarios associated with the initiating event of inadvertent operation of the top ECCS trip valve
  - Scenarios associated with the initiating event of inadvertent operation of the side ECCS trip valve
- Group B:
  - Scenarios associated with initiating events other than loss of DC power, inadvertent operation of the top ECCS trip valve, and inadvertent operation of the side ECCS trip valve.

The CDF of each group were summed. Fig. 8 presents the normalized CDF values of Group A and B according to the number of MP valves. The CDF sum for each group was normalized by dividing each value by the Group A CDF sum for the two MP valves case.

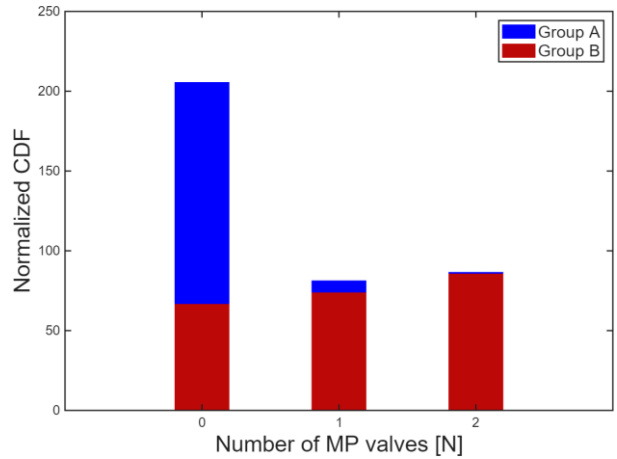


Fig. 8 Normalized CDF of Group A, B to the Number of MP Valves

In Group B, the CDF tended to increase as the number of MP valves increased, indicating that an increase in the number of MP valves raises the failure probability of intended ECCS opening and thereby increases the CDF associated with the relevant events. In contrast, in Group A, the CDF decreased as the number of MP valves increased, which is presumed to result from the prevent of unintended ECCS opening with increasing number of MP valves. However, even in Group A, there remains the possibility that an increase in the number of MP valves may increase the failure frequency of intended ECCS opening required for accident mitigation. To examine this more clearly, Group A was classified according to whether MP valve opening failure was included.

- Group A-1:
  - Group A scenarios involving failure of intended ECCS opening due to MP valve opening failure
- Group A-2:
  - Group A scenarios not involving failure of intended ECCS opening due to MP valve opening failure

In addition, the CDFs of Group A-1 and A-2 for each valve were normalized by dividing each value by the Group A-2 CDF for the two MP valves case.

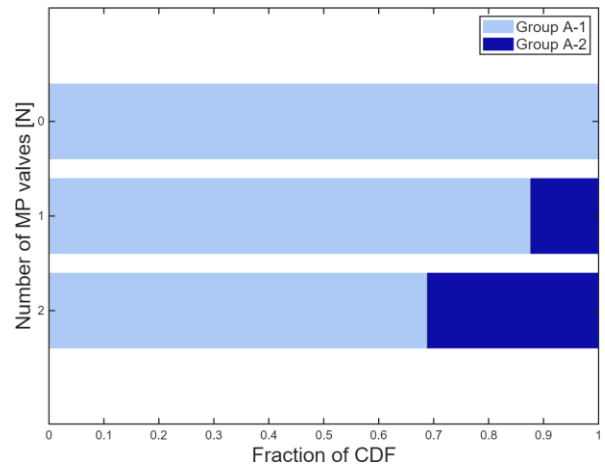


Fig. 9 Fraction of CDF of Group A-1, A-2 to the Number of MP Valves

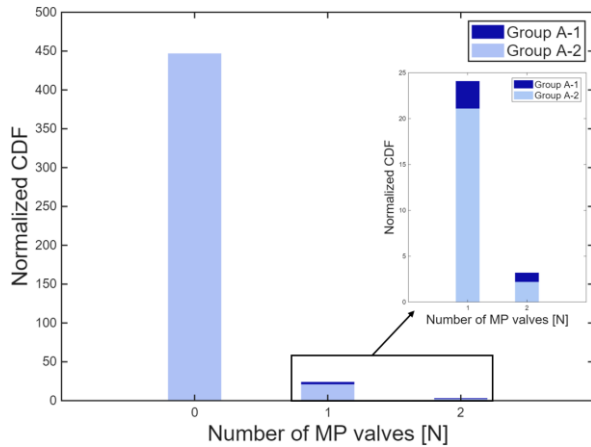


Fig. 10 Normalized CDF of Group A-1, A-2 to the Number of MP Valves

As shown in Fig. 9, when the internal composition of Group A was examined, the fraction of scenarios in which core damage occurred due to MP valve opening failure was found to increase with the number of MP valves. Although the relative fraction of A-2 within Group A increased as the number of MP valves increased, as shown in Fig. 10, comparison of the one MP valve and two MP valves cases showed that the absolute CDF of A-2 decreased because the MP valves reduced the frequency of unintended ECCS opening.

When comparing the cases with zero and one MP valve, the reduction in CDF due to the decreased frequency of unintended ECCS opening was judged to be greater than the increase in CDF caused by the higher failure frequency of intended ECCS opening, resulting in a lower CDF for the one MP valve case. Therefore, the installation of a MP valve was found to effectively reduce the CDF by decreasing unintended ECCS opening. In contrast, when comparing the cases with one and two MP valves, the additional risk reduction effect associated with preventing unintended ECCS opening is relatively limited, whereas the failure frequency of intended ECCS opening increases more significantly as the number of valves required to open during an accident increases, ultimately resulting in an increase in CDF. Therefore, the results of the quantitative risk assessment indicate that the two MP valves design cannot be regarded as providing a markedly greater safety improvement than the one MP valve design.

## 5. Conclusions

In this study, a PSA-based evaluation was performed for an water-cooled SMR adopting an ECCS design that utilizes primary coolant recirculation for accident mitigation, in order to assess the impact of applying the single-failure criterion to the MP function by arranging MP valves in series. The results showed that, as the number of MP valves increased, the CDF decreased in

terms of preventing unintended ECCS opening, However, the number of valves required to open also increased, leading to failures of intended ECCS opening and a corresponding increase in CDF. In particular, although the difference in total CDF between the one MP valve design and the two MP valves design was not large, the CDF for the two MP valves case was slightly higher than that for the one MP valve case. Therefore, applying the single-failure criterion to the MP function may not improve reactor safety from a risk perspective.

This study is a preliminary investigation conducted using a hypothetical reactor rather than a specific reactor design; therefore, the results are valid only under the reactor conditions assumed in this study. Accordingly, it is difficult to generalize these results to all reactors equipped with MP valves. In addition, the failure rate data for the MP valve itself involve considerable uncertainty. Therefore, the results of this study should be interpreted as preliminary study with these limitations, and further studies are needed that incorporate reactor-specific design characteristics and more reliable failure data.

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