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

Review of Failure Modes and Effects of IAB Valves in NuScale

Donghwan Choi, Hyungdae Kim, Eunhee Jang, Gyunyoung Heo*
Department of Nuclear Engineering, College of Engineering, Kyung Hee University, Yongin, Republic of Korea
Corresponding author: gheo@khu.ac.kr

***Keywords: NuScale, ECCS valve, IAB valve, Failure Modes and Effects**

1. Introduction

Global SMR development is actively progressing, including the development of innovative-Small Modular Reactor (i-SMR) in South Korea. Among the innovative safety system concepts being proposed, one notable example is the passive Emergency Core Cooling System (ECCS) [1]. This study was conducted using the U.S. NuScale design, for which relatively extensive design data has been disclosed, to analyze how the key valves constituting the passive ECCS system can be reflected in the Probabilistic Safety Assessment (PSA) model.

The objective of this study is to realistically calculate and incorporate the reliability of NuScale ECCS valves into the PSA model. This is achieved by identifying the malfunction status of the valves comprising the ECCS using an Event Tree (ET) and then expressing the results through a Fault Tree (FT). Since the above content could not be found in publicly available NuScale materials, this study aims to contribute to the domestic SMR risk assessment through this research.

In the ET for internal events presented in Chapter 19 of NuScale's Final Safety Analysis Report (FSAR), it was observed that the heading "ECCS open" is included throughout [2]. Additionally, it was confirmed that the "ECCS open" heading functions as the ultimate coolant circulation mechanism. However, in the initiating event group for Loss of Coolant Accident (LOCA), one event includes the spurious opening of the ECCS valve. Furthermore, in the sensitivity analysis table, there is a statement: "ECCS opening on low differential pressure – Core Damage Frequency (CDF) increase by a factor of 2." This indicates that the proper operation of the ECCS valve plays a critical role in the safety of the module.

To address this, NuScale has implemented an additional Inadvertent Actuation Block (IAB) valve in the ECCS valve configuration to reduce the frequency of spurious ECCS valve openings during normal operation. The IAB valve is designed as a passive system that operates based on the pressure difference between the Reactor Pressure Vessel (RPV) and the ECCS valve. Additionally, among the ECCS valve components, only the trip valve and reset valve are designed as solenoid valves. This fail-safe design ensures that even in the event of a power loss, changes in pressure alone can activate the IAB valve and the main valve.

While the additional installation of the IAB valve offers advantages, its complex interactions with other valves, unlike the original configuration, raise concerns about whether such interactions could hinder accident mitigation. Therefore, this study analyzes these potential issues.

2. Valve Operations [3]

To understand the interactions between the valves, it is necessary to first comprehend the function of the ECCS and the roles and operating principles of the valve assemblies that constitute it, namely the Reactor Vent Valve (RVV) and Reactor Recirculation Valve (RRV).

The ECCS is a system designed for coolant circulation during accident conditions by releasing the isolation between the reactor vessel (RV) and the containment (CNT), allowing natural circulation of the coolant. The ECCS is activated under two conditions: low pressure in the reactor coolant system (RCS) (below 800 psi, 5.5 MPa) or high-water level in the containment (above 252 in, 6.4 m). When these conditions are met during an accident, the ECCS valves (RVVs and RRVs) open, enabling the natural circulation of the coolant.

The ECCS valve assembly consists of four valves: the main valve, the IAB valve, and two solenoid valves (trip and reset valves). The reset valve connects fluid from the Chemical and Volume Control System (CVCS) to supply pressure inside the ECCS valve. It opens only when fluid is supplied and remains closed under normal conditions with a fail-close state. The trip valve functions to depressurize the ECCS valve by connecting it to the CNT during accident conditions; it remains closed under normal conditions and has a fail-open state.

The main valve opens based on the pressure difference between the main chamber and the CNT. Under normal conditions, the ECCS internal pressure compresses a spring to keep the main valve closed. The IAB valve remains open during normal operation to allow pressure sharing between the main chamber and the ECCS. It operates based on the pressure difference between the RPV and the ECCS valve. When this pressure difference exceeds 1300 psia (9 MPa), the IAB valve's spring is compressed by the RPV pressure, cutting off the pressure connection between the main chamber and the ECCS valve.

If an event occurs where the power to the solenoid valves (trip valve, reset valve) is lost, the (1) IAB valve closes due to the increase in the pressure difference across the IAB caused by the pressure reduction inside the ECCS valve, isolating the pressure-sharing in the main chamber, preventing the main valve from opening. This ensures that the situation does not escalate into a further LOCA event. However, unlike a power malfunction event, in accident scenarios such as LOCA, where the valve must open, the pressure difference across the IAB valve decreases as the RPV pressure drops. (2) This causes the IAB valve to open. Subsequently, the increased pressure in the CNT, along with the force from the compressed spring, leads to the (3) opening of the main valve, enabling the ECCS function of natural coolant circulation. The schematic of NuScale's ECCS valve is shown in Fig 1.

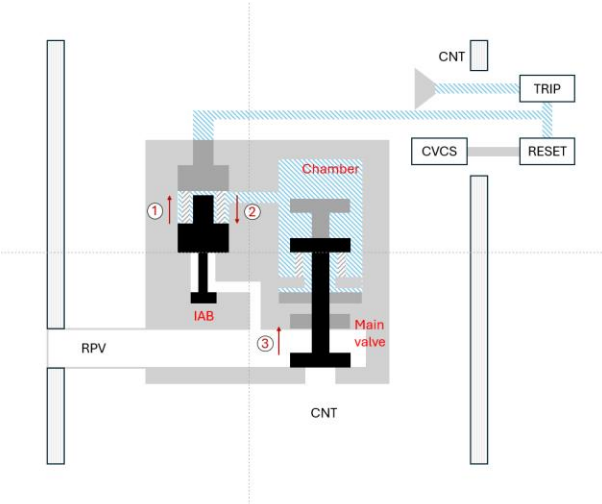

Fig. 1. Schematic of ECCS valve operations

3. Failure modes and effects analysis for ECCS valves

The IAB valve serves to prevent a power malfunction situation from leading to a LOCA situation as described above, thus reducing the frequency of initiating events.

Next, an analysis was conducted on cases where ECCS operation fails, specifically when the valve does not open, due to the additional installation of the IAB valve under accident conditions. In accident scenarios, the successful operation of the ECCS is classified when at least one RVV and at least one ERV are open. Therefore, the failure case is defined as the situation where the ECCS valve does not open.

The analysis focused on whether the ECCS valve operates normally and opens according to the failure status of the four valves that make up the ECCS. The situations where the valve does not open can be broadly classified into two categories: one where the main valve itself fails and does not open, and another where depressurization of the main chamber does not occur, preventing the main valve from opening due to insufficient pressure difference.

Therefore, excluding the failure of the main valve itself, cases were analyzed using an ET by reflecting the malfunction status of the remaining three valves. The ET is structured with headings for the opening of the reset valve and trip valve, as well as the two operating modes of the IAB valve, to represent all possible scenarios. The ET is shown in the following Fig 2.

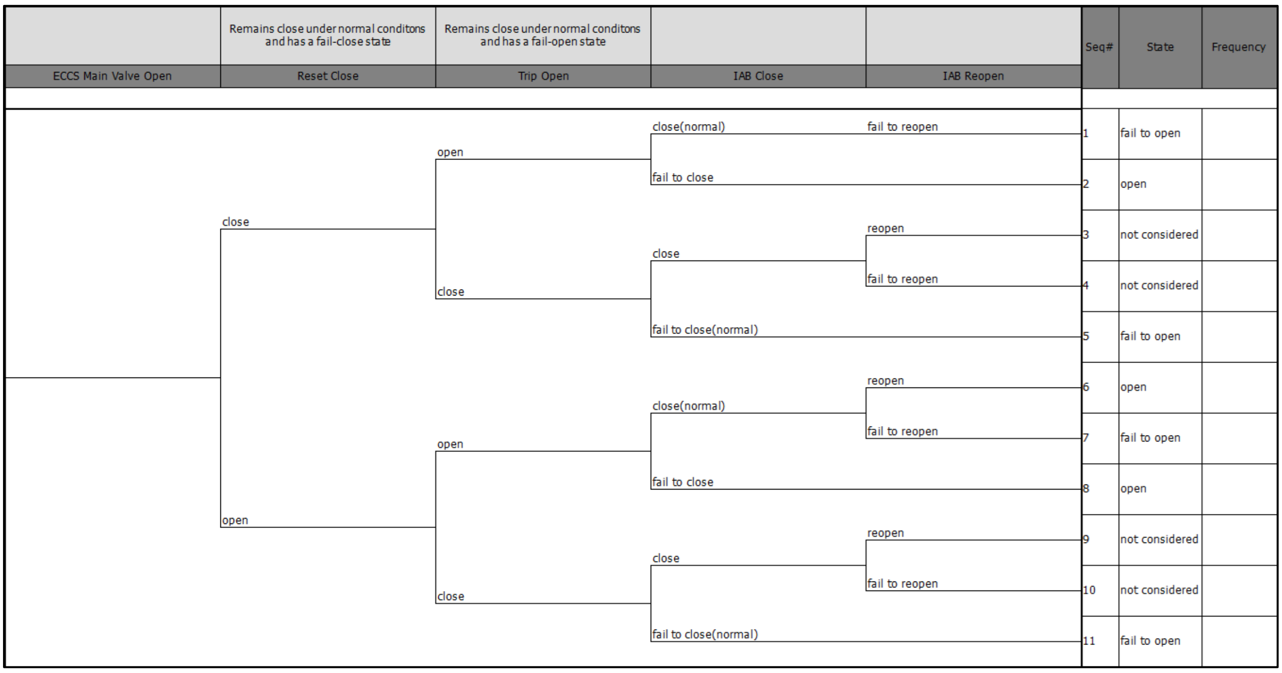

Fig. 2. Logic diagram for Functionalities of ECCS Valves

Seq 1)

The failure of a IAB valve can be categorized into two cases: when the valve fails to close despite an increasing pressure differential, and when a valve that has closed due to a pressure differential fails to reopen when the differential decreases.

Seq 1 refers to a failure mode of the IAB valve, where the valve, which should reopen when the differential pressure decreases after initially closing due to a pressure difference, fails to do so. The IAB valve closes when reactor trip occurs, as the opening of the trip valve causes a pressure drop within the ECCS. At the moment the IAB valve operates, the pressure in the main chamber undergoes its first pressure reduction.

The fail-to-reopen scenario of the IAB valve occurs in this condition. Under normal operation, the IAB valve would reopen, allowing further depressurization of the main chamber, which enables the valve to open. However, in a malfunctioning scenario, the pressure in the main chamber remains fixed, preventing the second stage of depressurization. As a result, the depressurization of the main chamber fails, leading to the failure of the main valve to open.

Seq 2)

Seq 2 refers to a failure of the IAB valve, where the valve that should close when the pressure difference increases fail to do so. In this case, as the trip valve opens, the pressure of the ECCS valve decreases. Under normal circumstances, the IAB valve should close to isolate the pressure boundary, allowing the main chamber to maintain a partially depressurized state. Subsequently, as the RPV pressure decreases, the IAB valve should open, further lowering the main chamber pressure to the CNT pressure before fully opening.

However, in an accident scenario, since the condition of main chamber depressurization is met, the main valve opens as intended. While the valve successfully opens, its premature opening during an accident may interfere with the operation of other safety systems, negatively affecting overall accident mitigation. Therefore, in addition to analyzing the valve opening itself, it is necessary to conduct a further analysis of accident progression based on the timing of the opening.

Seq 3)

Seq 3 corresponds to the case where the trip valve fails while the IAB valve operates normally.

Due to the failure of the trip valve, pressure reduction does not occur, and the IAB valve remains in its initially open state without any further progression. This is because the IAB valve operates by compressing a spring at its top to close, making it physically impossible for the valve to close on its own due to a malfunction.

Therefore, in the scenario where the trip valve fails, the possibility of the IAB valve closing was not considered.

Seq 4)

As in Seq 3, the case where the IAB valve closes in a situation where the trip valve has failed was not considered, as it is physically impossible.

Seq 5)

Seq 5 represents a scenario where the trip valve fails and the IAB valve does not close.

In cases where the trip valve functions properly, the closing of the IAB valve follows the normal sequence. However, if the trip valve fails and pressure reduction does not occur, the IAB valve cannot close, making its open state the expected behavior under these conditions.

Since the trip valve does not open, pressure within the ECCS valve does not decrease, leading to the failure of main chamber depressurization. As a result, the main valve does not open.

Seq 6)

Seq 6 represents a scenario where the reset valve fails and remains open, while the trip valve and the IAB valve function normally.

The failure of the reset valve refers to a case where a valve that should remain fail-closed opens independently. However, the impact of this failure is minimal because the dominant effect comes from the pressure reduction caused by the trip valve opening and its connection to the CNT.

Therefore, even in case of a single reset valve failure, the main valve still opens normally.

Seq 7)

Seq 7 describes a situation where the reset valve, which should fail-close, remains open, and the IAB valve fails to reopen after closing due to an increased pressure differential. This sequence progresses similarly to Seq1.

Due to the trip valve opening, the pressure within the ECCS decreases, causing the IAB valve to close. At this point, the main chamber maintains the reduced pressure. During the accident scenario, the pressure in the CNT does not increase enough to exceed the pressure in the main chamber, resulting in the main valve failing to open.

Seq 8)

Seq 8 represents a scenario where the reset valve, which should remain fail-closed, opens, while the IAB valve fails to close despite the increased pressure difference and remains open.

In this situation, as the trip valve opens, the pressure within the ECCS decreases. Since the IAB valve does not close, the pressure in the main chamber continues to decrease. As a result, the main valve opens normally. However, this sequence, like Seq2, also requires additional analysis of the accident progression due to premature opening.

Seq 9)

Seq 9 represents a scenario where the reset valve, which should remain fail-closed, opens, the trip valve, which should remain fail-open, does not open, and the IAB valve closes but then reopens.

Like Seq 3, since the trip valve remains closed, pressure within the ECCS does not decrease. Under these conditions, it is physically impossible for the IAB valves to malfunction by overcoming the force of the spring and the high pressure to close. Therefore, this case was not considered.

Seq 10)

For the same reason as Seq 9, this case was deemed physically impossible and was not considered.

Seq 11)

Like Seq 5, in this scenario, the reset valve remains open, and the trip valve fails to open, preventing depressurization within the ECCS. The IAB valve remains open, and since the pressure in the main chamber does not decrease, the main valve fails to open.

By analyzing each sequence in the ET of Fig. 2, sequences leading to main valve opening failure due to main chamber depressurization failure were identified. The review confirmed that the normal operation of the ECCS valve is determined independently of the reset valve, and it fails when the trip valve malfunctions and the IAB valve, after closing, fails to reopen under the given conditions.

Therefore, when representing the sequences leading to ECCS valve operational failure as basic events in the FT, the failure of ECCS valve operation can be expressed as an OR gate in the FT. This consists of the main valve opening failure due to an intrinsic defect, depressurization failure caused by the trip valve malfunction, and the case where the IAB valve successfully closes but subsequently fails to reopen.

4. Conclusions

NuScale reduced the frequency of unintended valve openings by incorporating the IAB valve into the ECCS valve design. This study primarily aimed to analyze the impact of valve interaction changes on operational scenarios under accident conditions resulting from the addition of the IAB valve to the ECCS valve. Through this analysis, the study sought to incorporate more realistic reliability values into the PSA analysis.

ECCS operational failure can be classified into two categories: failure due to the main valve's intrinsic defect and failure to achieve operating conditions caused by the depressurization failure of the main valve chamber. To analyze the impact of the additional installation of the IAB valve on the case of main chamber depressurization failure, an ET method was employed to represent scenarios based on the presence or absence of valve malfunctions.

The analysis results indicated that the additionally installed IAB valve affects ECCS valve opening failure. The IAB valve operates in two stages: closing when the pressure increases and reopening when the pressure decreases. It was confirmed that if the second stage, the reopening process, fails, it leads to ECCS valve opening failure.

Based on these findings, the FT representation of ECCS operational failure was analyzed, revealing that it can be described as an OR gate consisting of the main valve defect, the failure of the trip valve to open, and the failure of the IAB valve to reopen. The FT representation is shown in Fig. 3.

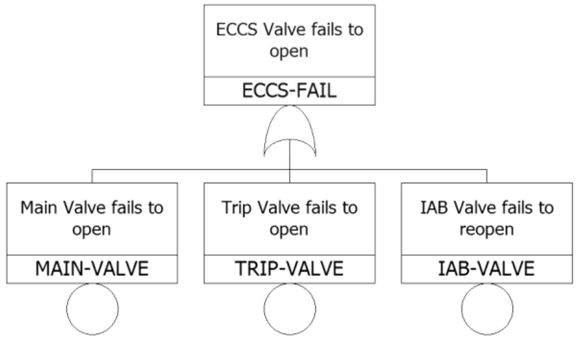

Fig.3. Expected FT for ECCS Failures

ACKNOWLEDGMENT

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).

We would like to express our sincere gratitude to Mr. Jinhee Park in Korea Atomic Energy Research Institute, specifically reviewing the valve failure mechanisms.

REFERENCES

[1] International Atomic Energy Agency, “Advances in Small Modular Reactor Technology Developments”, 2022.

[2] NuScale Power LLC, “NuScale Standard Plant Design Certification Application, Revision 5”, 2020.

[3] Hruškovič, Jan, et al. "Design Consideration of ECCS Valve for Integral Type SMR.", 2024.