Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 9-10, 2024

Design Consideration of ECCS Valve for Integral Type SMR

Jan Hruškovič, Youngjae Park†, Youcho Choi, Young Seok Bang, Seong-Su Jeon and Soon-Joon Hong
FNC Technology Co., Ltd., 32F, 13 Heungdeok 1-ro, Giheung-gu, Yongin-si, Gyeonggi-do, 16954, Republic of Korea
†Corresponding author: ypark1227@fnctech.com

***Keywords: SMR, NuScale, ECCS valve, passive system, nuclear safety**

1. Introduction

Despite recent significant advancements in the development of Small Modular Reactors (SMRs) and related technologies, there are still some technical issues that challenge the industry. One of them is development and manufacturing of novel components, such as the emergency core cooling system (ECCS) valve. [1]

In conventional PWR power plants, ECCS consists of several safety injection tanks and pumps, which supply borated water into the reactor core in case of loss of coolant accidents (LOCAs) and remove the core decay heat. On the other hand, SMRs introduce simplified design, advanced passive safety features and decreased number of components. In case of NuScale SMR, ECCS is utilized by valves located at the top of the reactor vessel and above the reactor core. Upon activation, natural circulation is established and reactor core can be cooled without any need for active components requiring electrical power, as shown in Figure 1. [2, 3]

This paper is focused on review and description of the NuScale ECCS valve design and its function. Based on the available patent and design certification documents, general design considerations are listed.

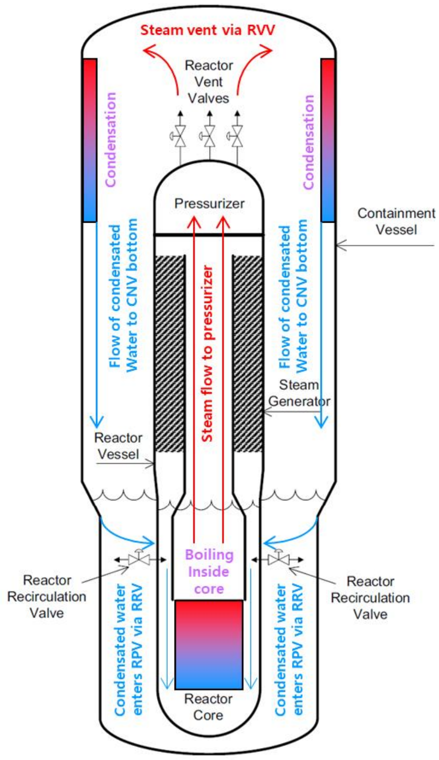

Figure 1 Schematic of ECCS and natural circulation [4]

2. Emergency Core Cooling System

The NuScale SMR is designed to allow for inherent passive safety and defense-in-depth with fail-safe safety systems. Unlike conventional large PWR plants, it is able to safely shut down and cool-down for unlimited amount of time without any operator action, or need for an active system utilizing AC or DC power.

There are three primary safety systems present: decay heat removal system (DHRS), emergency core cooling system (ECCS), and containment system (CNT), which serves as the ultimate heat sink by submerging the containment vessel in the reactor pool. [3]

NuScale ECCS consist of reactor vent valves (RVVs) attached on the top of the pressurizer, allowing steam to be vented from the reactor pressure vessel (RPV) into the containment vessel (CNV), where it condenses on CNV wall; and reactor recirculation valves (RRVs) located approx. 6 ft above the core, which allow this condensated water to re-enter the RPV and therefore ensure the core decay heat removal based on natural circulation. Heat dissipated to the CNV wall during condensation is then transferred by conduction through the wall to the ultimate heat sink. [4, 5]

2.1 Function of NuScale ECCS

The NuScale ECCS is designed as a passive system and is able to perform its safety function for at least seven days after a design basis event. Although ECCS does not require any operator action for its operation, manual actuation is also possible from the control room. In the NuScale design, ECCS serves three purposes:

1. During normal operation, when all ECCS valves (RVVs and RRVs) are in closed position, ECCS is part of the reactor coolant pressure boundary (RCPB) and prevents the coolant leakage outside of the primary system.
2. During accident conditions, such as LOCA, when RCS cannot be cooled by other means, ECCS provides cooling to the reactor core with sufficient decay heat removal capacity, ensuring the fuel to be fully covered by the coolant.
3. ECCS provides low temperature overpressure protection (LTOP) for the RPV to prevent brittle failures (exact conditions such as RCS pressure and temperature vary based on the NuScale SMR version but in general LTOP applies during start-up and shutdown conditions).

Each NuScale ECCS valve consists of following four parts - main valve, inadvertent actuation block (IAB) and two solenoid pilot valves (trip and reset valve). The valve assembly is placed between RPV and containment, and the main valve is closed during nominal power operation by pressurization of the main valve chamber.

Unlike other valves used in conventional LWR plants with simple design, whose purpose is to depressurize primary system (i.e. pilot operated safety relief valve), this valve can be prevented from opening during power operations upon ECCS actuation by the IAB feature. When the pressure difference between primary system and containment is high, opening of the valve could threaten CNV integrity by releasing high-energy and high-pressure steam. Therefore, if the pressure difference between RCS and CNT is above certain setpoint and ECCS is actuated by activating the trip valve, the IAB remains closed. As a result, the flow path from main valve chamber to the containment is blocked, preventing the chamber from depressurization and consequent opening of the main valve. Since the IAB arming setpoint is above limiting RPV pressure for LTOP operating conditions, IAB does not prevent actuation of ECCS valve during low temperature conditions. This IAB feature is a patented innovative solution. [4, 5, 6]

2.2 Principle of NuScale ECCS valve

The patent for NuScale ECCS valve, *"Inadvertent actuation block valve for a small modular nuclear reactor"* [6], describes two different valve embodiments, whose function is described in the following part. In both cases, the ECCS valve assembly is attached to the RPV and the pilot valve assembly, including trip and reset valves, is located outside of the containment.

In the first embodiment of ECCS valve, RCS is in fluid communication with the main valve as well as the bottom part of IAB (first inlet). The main valve chamber is then in fluid communication with the second inlet of IAB. When the IAB is open, fluid (water or steam) can flow from the main valve chamber through IAB outlet to pilot valve assembly. Reset valve is connected to external fluid source, chemical and volume control system (CVCS), its purpose is to close the main valve during nominal power operation and it is designed as fail-close valve in case the power is lost. Trip valve is then connected to CNT and when activated, fluid can flow from the main valve chamber via IAB (if open) to CNT, depressurizing the valve chamber. This causes the main valve to open and allow flow from RCS directly to CNT (in case of RVV, or in opposite direction in case of RRV).

To prevent the main valve from opening upon high pressure difference between the RPV and CNT during power operation, the IAB is in fluid communication with RCS by its first inlet and is equipped with a preloaded spring, which under low pressure difference holds the IAB in open position. When the pressure difference is above setpoint, fluid from RCS imposes pressure on the IAB, suppressing the spring and closing the flow path from main valve chamber to the pilot valve assembly. This as a result prevents the main valve chamber from depressurization and subsequent main valve opening.

The main valve is also equipped with a preloaded spring and when chamber is pressurized, fluid imposes pressure on the main valve disc, suppressing this spring and subsequently closing the main valve. Upon chamber depressurization, spring opens the main valve and fluid can flow from the RPV directly into the containment.

The main valve chamber can be pressurized either from the external fluid source via reset valve, or directly from RCS through the main valve piston inflow ports.

Schematic of the first embodiment of the NuScale ECCS valve is shown in Figure 2.

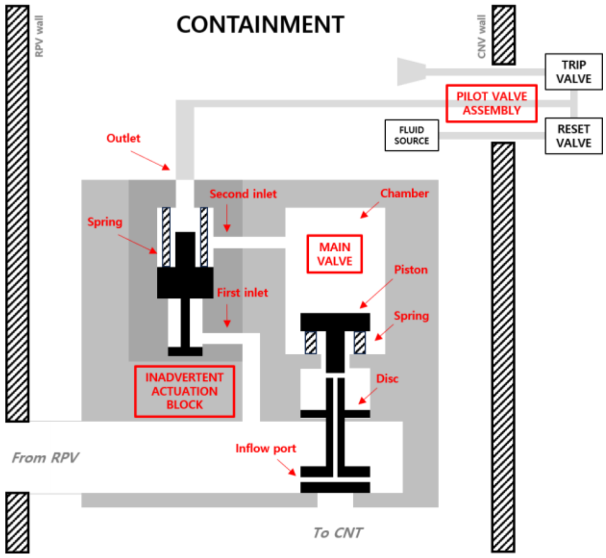

Figure 2 Schematic of first embodiment of the ECCS valve

Principal function of the second valve embodiment is similar to the first one and differs in the IAB placement, inlet and outlet connections. There are also metal bellows placed inside of IAB, separating fluid communication between the first and second inlets. First inlet (in the bottom) is connected to the RPV (RCS fluid), same as in the first embodiment. Second inlet, placed outside of the metal bellows, is connected directly to the trip valve and IAB outlet is connected to the containment. There are also inflow ports installed inside the IAB, which connect the second inlet with outlet, when the IAB is open.

Other parts of the second embodiment of the ECCS valve are in principle similar to the first embodiment, including the main valve (with its chamber, spring and disc), and the pilot valve assembly (consisting of a trip and reset valves and an external fluid source).

2.3 NuScale ECCS valve operation

Firstly, operation of the first embodiment is described. During normal operation, when RCS is pressurized, fluid source supplies coolant from CVCS through the reset valve into IAB. This fluid can flow into the main valve chamber and impose pressure on the main valve disc, which forces the main valve to remain closed. Therefore, flow between the RCS and CNT is prevented.

When the ECCS is actuated (by actuation of the trip valve) but pressure difference between RCS and CNT is above setpoint, main valve will not open. This is caused by RCS coolant, which imposes pressure on the IAB via its first inlet and suppresses force of the preloaded IAB spring, closing the IAB. So, the flow path from main valve chamber to the pilot valve assembly through IAB is closed. The main valve chamber remains pressurized and main valve closed, thanks to inflow ports inside the main valve piston, connecting RCS with the main valve chamber. In this case, trip valve is open (by ECCS actuation) but as IAB is fully closed, the trip valve does not have any effect on the main valve operation.

Lastly, when ECCS is actuated and pressure difference between RCS and CNT is below setpoint, IAB opens, allowing the main valve chamber to depressurize and subsequently open the main valve. In this case, steam can be vented from the pressurizer into CNT via RVV and condensed water can re-enter the RPV through RRV. Natural circulation is established and core can be cooled.

The function of second embodiment of ECCS valve is following. During normal operation, it operates in same way as in case of the first embodiment. When the ECCS is actuated during nominal operation and the pressure difference between RCS and CNT is above setpoint, main valve will also not open. In the second embodiment, RCS coolant imposes pressure on the IAB through the first inlet, suppresses the preloaded IAB spring, which causes IAB to close and prevent any flow from the trip valve through IAB inflow ports into the containment. Also, thanks to inflow ports inside the main valve piston, the main valve chamber remains pressurized and main valve therefore closed.

When the pressure difference between RCS and CNT is below setpoint and ECCS is actuated, preloaded spring opens the IAB, allowing flow path from the main valve chamber, via trip valve, through IAB inflow ports inside the containment, which depressurizes the main valve chamber and as a result opens the main valve. [6]

3. ECCS Valve Design Consideration

There are many requirements and considerations for design and development of an ECCS valve. Generally, for whole ECCS as a safety system, and also specifically for safety valve as part of RCS, placed on the RPV.

In this part, the general ECCS acceptance criteria according to 10 CFR 50 are briefly reviewed and based on the related chapters of NuScale FSAR documentation, the ECCS valve design considerations are described.

3.1 General ECCS acceptance criteria

According to 10 CFR 50.46 (Acceptance criteria for ECCS for light-water nuclear power reactors), each pressurized light-water nuclear power reactor fueled with UO_2 enclosed in zircaloy cladding must be provided with ECCS designed with sufficient capacity, so that during postulated loss of coolant accidents, five criteria are met. Those include limits on the maximum peak cladding temperature, cladding oxidation, hydrogen generation, coolable geometry of the fuel and long-term cooling.

In general, ECCS shall be capable of sufficient cooling to the reactor core during LOCA events, ensuring the fuel rods fully submerged in subcooled coolant, without any significant degradation to the fuel and its cladding.

3.2 Design considerations based on FSAR

To satisfy cooling capability during LOCA, ECCS is designed conservatively with sufficient capacity and safety margin, even if a single valve fails to open. Since ECCS valves are part of the RCS, attached on the RPV and serve as a safety system, its design has to be reflected from many perspectives. Operating parameters such as design pressure, temperature, flow area, or minimum flow rate at certain pressure are just one part of the design. Other considerations, such as material properties, connected instrumentation and control (I&C), testing and inspections, valve operation and setpoints implemented in ESFAS shall be determined upon design. Also, related probabilistic and deterministic safety analyses shall be evaluated for the valve separately and for the whole reactor system during various operating conditions.

Based on the NuScale FSAR review (especially chapters 1, 3, 5, 6, 7, 15 and 19), some of the most important considerations can be summarized. Following list of items contains available parameters, properties and other items related to ECCS valve design:

(1) ECCS valve parameters and properties
   (a) Design parameters, such as internal (RCS) and external (CNV) pressure or temperature;
   (b) Local operating conditions, such as harsh environment due to borated coolant and other degrading mechanisms (vibration, corrosion, erosion, stress, or water hammer);
   (c) Relief capacity to satisfy ECCS acceptance criteria and ensure decay heat removal with sufficient margin and also while considering the single failure criteria;
   (d) Suitable materials for valve and its parts with respect to operating parameters, conditions and environment to ensure valve integrity;
   (e) Placement (location) and connection to the RPV, so that coolant level in RPV is maintained above the core and fuel remains covered at all times, natural circulation is established after system is actuated, no damage is caused by jet impingement or pipe whip, and regular inspections are possible;
   (f) Connection to related equipment, such as pilot and reset valves or I&C, to control the valve position, or monitor valve parameters;
   (g) Reliable function for all principal functions, such as decay heat removal during LOCA and low temperature overpressure protection;
   (h) Other plant-specific properties.
(2) Valve testing
   (a) To demonstrate function at reactor operating pressures and temperatures;
   (b) To demonstrate function in borated coolant;
   (c) To demonstrate the fail-safe design during

exercise test and to conduct stroke time measurement;
- (d) To test the minimum flow capacity;
- (e) To test the inadvertent block function;
- (f) To test the main and block valve for leakage;
- (g) To test pilot valves for leakage.

(3) Instrumentation and control
- (a) Connection of sensors, actuators, solenoids;
- (b) Engineered safety feature actuation system (ESFAS) – measured variables, their limits, number of channels, logic and automated functions;
- (c) Valve operation - automatic by ESFAS and manual by operator from the control room;
- (d) Monitoring of valve position and parameters;

(4) Probabilistic risk assessment (PRA)
- (a) Evaluation of likelihood of a spurious partial opening event in ECCS valve;
- (b) Estimation of the frequency of spurious valve opening and probability of single ECCS valve fails to open upon on demand;
- (c) Evaluation of valve pressure locking, to prevent opening at high pressures;
- (d) Determination of the success criteria for successful ECCS operation, such as required number of valves to open;
- (e) For events requiring ECCS operation, evaluation of probability and consequences of main valve, and/or pilot valves to open.

(5) Transient and accident analysis
- (a) Operation during loss of coolant accidents;
- (b) Analysis of inadvertent openings of ECCS valve including sensitivity analysis.

Although this list contains extensive number of items, it is worth noting that it is plant-specific and exact details and parameters for the ECCS valve design strongly depend on the target system, its parameters, operating conditions, and the design and function of the whole ECCS. Also, it is important to design such valve and related equipment in compliance with intellectual properties, such as existing patents.

4. Conclusions

In this paper, the design, function and operation of NuScale ECCS valve were described, based on the final safety assessment report and related patent.

The inadvertent actuation block (IAB), which is an innovative feature of this valve, prevents main valve from opening upon ECCS actuation, in case of high pressure difference between RCS and CNT during reactor power operation, to protect containment vessel and maintain its integrity. Due to a limited number of available information from the design documents and lack of published research related to this ECCS valve with IAB, it is very important to understand its design and function properly. This paper brings insight into the ECCS valve design and can be useful in future research and development for SMRs and related systems.

Acknowledgement

This study was supported by the Innovative Small Modular Reactor Development Agency grant funded by the Korean Government (Ministry of Science and ICT, MSIT) (No. RS-2023-00321928).

REFERENCES

[1] International Atomic Energy Agency, "Advances in Small Modular Reactor Technology Developments", 2022.
[2] International Atomic Energy Agency, "Status Report – NuScale SMR (NuScale Power, LLC)", 2020.
[3] Welter K., Reyes J. N. Jr. and Brigantic A., "Unique safety features and licensing requirements of the NuScale small modular reactor", Frontiers in Energy Research, 2023.
[4] NuScale Power LLC, "NuScale Standard Plant Design Certification Application, Revision 5", 2020.
[5] NuScale Power LLC, "NuScale US460 Plant Standard Design Approval Application, Revision 1", 2023.
[6] O'Brien, Hugh S., and Velkoff, Jr., William Jeffrey. Inadvertent actuation block valve for a small modular nuclear reactor. United States: N. p., 2022.