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Areas of Regulatory Review Focuses on Passive Safety System Design

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1. Introduction

Currently, Small Modular Reactors (SMRs) are drawing high attention around the world and in consequence, various type of SMRs such as NuScale, SMART100, iSMR etc. have been being developed or under development. One of the common features of those SMRs is an introduction of Passive Safety System (PSS) to strengthen safety of the reactors.

In light of current circumstance, recently, Korea Institute of Nuclear Safety (KINS) has launched a long-term regulatory research project titled as "Study on Validation of the Consolidated Safety Analysis Platform for Applications of Enhanced Safety Criteria and New Nuclear Fuels" and initiated the research on performance/reliability evaluation methodologies and development of regulatory guide for PSS under this project. In 2021, as part of the research, regulatory practices of foreign countries have been analyzed and some regulatory focuses on PSS were identified [1] based on OECD/NEA-WGRNR [2] and WENRA-RHWG [3] reports.

Unfortunately, however, the previous study [1] didn't consider reports published by IAEA and US NRC even though both organizations have actively published many SMRs related documents and in some of them, regulatory practices on PSSs are well described.

Therefore, in the present study, the reports published by IAEA SMR Regulators' Forum (IAEA Forum), and Design Specific Review Standards (DSRSs) and Safety Evaluation Reports (SERs) for NuScale reactor by US NRC are analyzed in detail to identify additional regulatory practices on PSS. Then, they are consolidated into the previous result [1] resulting "Comprehensive PSS Design Review Focus (CDRF)". In addition, "Evaluation Methods for Comprehensive PSS Design Review Focuses (EMCDRF)" are also suggested in the present study for safety analysis perspective.

2. Analysis on IAEA and US NRC Documents for Regulatory Practices on Passive Safety System

IAEA has organized IAEA Forum since 2014 and has been sharing regulatory knowledge and experience on SMRs among member states. The main goal of IAEA Forum is to improve the safety of SMRs through the identification of safety issues and the accumulation of knowledges in relation to SMRs regulatory review. Although IAEA Forum has published numerous reports so far, a recent report titled as "Small Modular Reactor Regulators' Forum Working Group on Design and Safety Analysis Phase 2 Report, June 2021 [4]" seems to be most relevant to the present study from a perspective of identifying PSS regulatory practice. Therefore, this recent report was analyzed in detail.

In addition, US NRC developed special DSRSs [5] for NuScale Reactor in 2016 to supplement the existing Standard Review Plan (SRP) and published SERs [6] by applying them for NuScale standard design application in 2020. Since NuScale reactor adopts several PSSs, DSRSs directly related to NuScale's PSSs were reviewed in the present study as well as the SERs relevant to these DSRSs in order to identify any regulatory practice on PSS. Several other DSRSs and their SERs which are believed to be relevant to safety analyses linked with the PSSs as well as newly added DSRSs and their SERs for NuScale reactor are also analyzed in the present study.

2.1 IAEA SMR Regulators' Forum Report

IAEA Forum report [4] consists of three chapters and its section 2.2 (Common Positions for Consideration in Design and Deployment of SMR Facilities) describes common regulatory positions of IAEA member states on PSS design. Those common positions can be summarized as follows.

Table 1: Common positions on PSS regulation [4]

A1. Identifying and Addressing Uncertainties in Performance Claims for First of a Kind Facilities
I1. To resolve performance uncertainties of a first of a kind facility with passive and inherent safety system, the follow factors should be considered. ① Results from substantiation activities (e.g. use of sufficiently validated computer model, experimental prototypical systems, integrated test facilities) ② Compensatory design enhancements (if required) ③ Proper control measures by the operator

④ Any additional activities necessary to demonstrate and/or support functional performance claims and to gather experience data I2. Since the performance uncertainties becomes bigger as the combination of interfacing inherent and passive design features grows, integrated tests need to be conducted both during the design process and the commissioning phase of the first of a kind facility for its design substantiations.
A2. Assessment of Reliability for Passive Systems in the Presence of Weak Driving Forces I1. Designers should establish clear criteria for characterizing the strength of driving forces of PSS and understand the conditions which lead driving forces to loss of its effectiveness or predictability. I2. Information obtained should be used to identify and understand failure modes that could impact the delivery of a safety function with sufficient reliability. I3. Designers should ensure that all parameters potentially affecting the delivery of a safety function are taken into account within the safety demonstration
A3. Optimization of the Use of Passive and Active Features in the Design Process I1. Subject to a prioritization which favors first inherent characteristics and then passive features or continuously operating systems over standby systems, any combination of active and PSS can be acceptable if defense in depth and safety design principles are met I2. Designer should document the approach for establishing optimization in the use of passive and active features.
A4. Applicability of the Single Failure Criterion to Provisions that include Passive and Inherent Characteristics I1. Designers should apply the single failure criteria in safety evaluations of PSSs in SMRs. I2. If compliance of the single failure criteria is not practicable, a demonstration that adequate reliability can otherwise be achieved should be presented. I3. The demonstration should account for all potential PSS failure modes and their evolutions in time in particular when driving forces are weak.
A5. Requirements for Diversity and the Treatment of Common Cause Failure I1. Redundancy, diversity and where practicable, physical separation should be employed in PSS design to mitigate common cause failures. I2. When PSSs are exclusively deployed in SMRs design, functional diversity should be considered with care. I3. Combined use of passive and active systems improves resilience to common cause failures since it may provide additional diversification.

※ A: Area; I: Item

2.2 US NRC DSRSs and SERs

NuScale reator deploys three PSSs such as Decay Heat Removal System (DHRS; DSRS 5.4.7 & DSRS BTP 5-4 and SER 5.4.4), Containment Heat Removal System (CHRS; DSRS 6.2.2 and SER 6.2.2) and Emergency Core Cooling System (ECCS; DSRS 6.3 and SER 6.3). Through reviewing those DSRSs and SERs relevant to DHRS, CHRS and ECCS, following regulatory practices on PSSs were identified

Table 2: Analysis on DSRSs and SERs for DHRS, CHRS and ECCS.

A1. Decay Heat Removal System (DHRS) I1. DSRS 5.4.7 & DSRS BTP 5-4 ① DHRS should comply with the single failure criteria. ② DHRS should cool down a reactor into the safe shutdown condition within a reasonable amount of time. ③ Injected boron should be well mixed during a natural circulation of DHRS. ④ DHRS should work properly with a minimum level and a maximum temperature conditions of reactor building pool. ⑤ Dynamic effects (flow instabilities, water/steam hammer) should not affect DHRS safety function. I2. SER 5.4.4 ① To verify that the fouling factor of DHRS condensation heat exchanger is selected correctly. ② To verify that negative effect of non-condensable gas is taken into account in DHRS design. ③ To verify that FPOT (First-Plant-Only Test) can be used for performance verification after DHRS installation. ④ To verify that the safe shutdown condition is well established based on PSS feature. ⑤ To verify that the surveillance requirement to monitor assumed DHRS level in the safety analysis exists. ⑥ To verify that water hammer occurring at the time of DHRS operation does not affect DHRS safety function.
A2. Containment Heat Removal System (CHRS) I1. DSRS 6.2.2 ① Surface fouling of inner and outer walls of containment vessel should be taken into account for evaluation of heat removal performance of containment vessel. ② Evaluation on ultimate heat sink design for containment heat removal should be conducted. ③ Accident-generated debris effect including loss of long-term cooling capacity should be assessed. ④ Non-condensable gas effect and surface effect (contamination, coating) should be considered

in coolant condensation inside the containment after reactor vent valves open. I2. SER 6.2.2 ① To verify that accident-generated debris does not affect long-term cooling capacity of CHRS. ✓ In relation with GSI-191 safety issue ✓ NuScale reactor was designed to minimize debris generation and chemical effect
A3. Emergency Core Cooling System (ECCS) I1. DSRS 6.3 ① PSSs including ECCS should be designed to maintain the safe shutdown condition for 72hrs without operator actions and non-safety class on-site and off-site powers. ② Effect of accident-generated debris and latent debris on clogging of debris screen and fouling of nuclear fuel including possibility of loss of long-term cooling capacity should be assessed. ③ Dynamic effects (flow instabilities, water/steam hammer) should not affect ECCS safety function. ④ ECCS should rule out any negative effects due to non-safety systems. I2. SER 6.3 ① To verify the effect of inadvertent operation of ECCS ② To verify that accident-generated debris does not affect long-term cooling capacity of ECCS. ✓ In relation with GSI-191 safety issue ③ To verify that boron precipitation does not affect the natural circulation in the reactor core. ④ To verify that water hammer does not affect ECCS safety function.

NuScale DSRS has special DSRS sections newly added to sections comparable to the existing SRP due to unique features of NuScale reactor. In the present study, some of the special DSRS sections and the comparable DSRS sections (DSRSs 15.6.6; 15.9.A; 15.1.2; 15.2.8; 15.6.5) and their SERs (SERs 15.6.6; 15.9.A; 15.1.2; 15.2.8; 15.6.5) related to safety analysis with the PSSs were also analyzed to identify regulatory practices on PSSs.

Table 3: Analysis on DSRSs and SERs related to safety analysis with PSSs.

A1. Inadvertent Operation of the Emergency Core Cooling System I1. DSRS 15.6.6 ① In spite of inadvertent operation of ECCS, minimum DNBR should be greater and equal to design limit of DNBR. I2. SER 15.6.6 ① To verify that an example of inadvertent operation of ECCS is properly selected for review. ② To verify that initial conditions and input parameters for safety analysis are properly selected to give a conservative result for minimum DNBR.
A2. Thermal Hydraulic Stability Review Responsibilities I1. DSRS 15.9.A ① Reactor core and related systems should be designed with enough margin to prevent undamped oscillations or other thermal hydraulic instabilities. ② Design to diagnosis and suppress oscillations with quick and reliable manner should be employed if potential oscillations cannot be avoided. ③ There should not exist other kinds of instability mechanism except density-wave instabilities. I2. SER 15.9.A ① To verify that the stability analysis covers normal operations (including startup and cooldown) and anticipated operational occurrences. ② To verify that design adopted to prevent instabilities is appropriate.
A3. Loss-Of-Coolant Accidents Resulting from Spectrum of Postulated Piping Breaks within the Reactor Coolant Pressure Boundary I1. DSRS 15.6.5 ① Boron precipitation should not affect coolable geometry and core flow. ② Change of natural circulation cooling flow due to accident-generated debris should be assessed. ③ ECCS natural circulation flow should be verified by experimental data. I2. SER 15.6.5 ① To verify that there is no fuel damage during LOCA by critical heat flux mechanism (Core is always covered with water even during LOCA). ② To verify that natural circulation cooling path and core flow are maintained during LOCA because boron precipitation does not occur. ③ To verify that boron coating due to boiling at the internal core structure does not lead to flow path blockage or degradation of cooling. ④ To verify that containment building pool temperature is assumed conservatively high to assess long-term cooling after LOCA from maximum temperature point of view. ⑤ To verify that non-condensable gas effect is considered in the long-term cooling after LOCA.

3. Identification of Comprehensive Passive Safety System Design Review Focuses and Their Evaluations

Having identified regulatory practices by analyzing IAEA Forum report [4], and US NRC DSRSs [5] and their SERs [6] for NuScale, those practices are consolidated into the previous research result [1] in the form of regulatory focuses on PSS to identify “Comprehensive PSS Design Review Focuses”. Since specific details of all process to draw them is given elsewhere [7], only the final result is shown below.

Table 4: Comprehensive Passive Safety System Design Review Focuses.

A1. Single Failure Criterion F1. Verify that the single failure criterion is applied to check valves installed in passive safety systems.
A2. Plant State F1. Verify that the safe shutdown state attained by the passive safety system operation is well defined and a time to reach the safe shutdown state is determined properly.
A3. Considerations on validation of performance F1. Verify that the application range of the computer program used to prove the performance of the passive safety system is appropriate, and conduct a validation test ~~if necessary~~ (consideration on the effects of reciprocal influence and scaling during validation tests).
A4. Simultaneous operation of many (multiple trains) systems F1. Evaluate the effect of simultaneous operation of many (multiple trains) passive safety systems on the performance of their safety functions by analytical method or demonstrative test.
A5. Simultaneous operation/optimization of active and passive systems F1. Evaluate the effects of simultaneous operation of the passive safety system and the active system (non-safety system) on the performance of their safety functions by analytical method or demonstrative test.
A6. Reliability F1. Functional failure should be considered in the reliability assessment of the passive safety system and the failure root causes are reflected in the reliability model. F2. When demonstrating the safety function of the passive safety system, all failure modes should be verified and any parameters affecting the safety function should be counted.
A7. Evaluation of the effect of malfunction F1. Evaluate the effects of malfunction and inadvertent actuation of the passive safety system.
A8. Commissioning/Periodic verification tests F1. Verify if commissioning tests on passive safety systems are done and make sure that passive safety systems are designed to accept periodic tests (especially for active components in passive safety systems) during plant operation.
A9. Operability F1. Operability of the passive safety system should be guaranteed through comprehensive analysis and operability evaluation of related components (check valve etc.)
A10. Considerations on verification of performance of a passive safety system with weak driving force F1. Evaluation of phenomena and parameters affecting the performance or failure of the passive safety system from the driving force perspective [non-condensable gas, leakage of the system, fouling factor of heat exchanger, surface effect (contamination, coating) on condensation, temperature and level of heat sink, initial system configuration (level)] F2. Environmental condition assessment (atmospheric temperature) F3. Application of margin concept to prevent Cliff-Edge Effect (consideration of aging effect) F4. Performance demonstration considering dynamic behavior F5. Evaluation of the effect of system arrangement on the isolation function of containment
A11. Internal and external hazards F1. The original safety function of the passive safety system should be maintained even if the environmental conditions under which the passive safety system is being operated has changed by internal and external hazards. (atmospheric heat sink, temperature-fire, piping configuration-earthquake)
A12. Considerations on human factors F1. From design, construction, and operation stages, consider the sensitivity of the passive safety system to human error. F2. Evaluation of the potential benefits or needs of operator intervention and the installation of the performance verification device for the passive safety system
A13. Reflection of operating experience F1. Reflect the operating experience by utilizing the results of preservice & in-service tests
A14. Considerations on diversity and common cause failure F1. Verify that the passive safety system and the active non-safety system with high reliability and operability perform safety functions in combination.
A15. Boron effect on natural circulation cooling F1. Verify that natural circulation flow path blockage or natural circulation cooling degradation do not occur by boron precipitation or boron coating phenomena when the passive safety system operates.
A16. Debris effect on natural circulation cooling F1. Verify that natural circulation flow path blockage or natural circulation cooling degradation do not occur by accident-generated debris and latent debris when the passive safety system operates.
A17. Flow instabilities F1. Verify that the passive safety system's safety function does not degrade by flow instabilities for normal operations (including startup, cooldown) and anticipated operational occurrences. F2. Verify that a design for monitoring flow instabilities reliably and quickly and suppressing them is employed if necessary.
A18. Water/steam hammers phenomena F1. Verify that the passive safety system's safety function does not degrade by water/steam hammer phenomena for normal operations (including startup, cooldown) and anticipated operational occurrences.

※ A: Area; F: Focus

Table 4 shows consolidated results for the regulatory focuses on the passive safety system from the present study and the previous study [1]. Titles and a paragraph in blue from Table 4 (**A5, A6, A14**) represent that these contents are identified from IAEA forum report. Titles in red (**A15~A18**) represent that these contents are identified from US NRC DSRSs and SERs for NuScale reactor. Paragraphs in green (**A1~A3, A8, A10, A14~A18**) represent that these contents are revised or newly introduced by consolidating the current and previous result [1].

Given comprehensive PSS design review focuses in Table 4, a specific way to evaluate each focus is proposed from safety analysis perspective. For example, as a specific evaluation method for "A1. Single Failure Criterion", it is proposed to verify that single failure criterion on check valves is applied to a passive safety system modelling for the safety analysis. Applying the same manner to other focuses, "Evaluation Methods for Comprehensive PSS Design Review Focuses" are identified in Table 5 below. Note that there are some items (**A8, A13, A14**) which can not be evaluated from the safety analysis perspective.

Table 5: Evaluation Methods for Comprehensive Passive Safety System Design Review Focuses.

A1. Single Failure Criterion E1. Is the single failure criterion applied to check valves during the safety analysis?	**R**
A2. Plant State E1. Is the safe shutdown state of a plant attained within the time defined by the passive safety system design after an accident?	**P**
A3. Considerations on validation of performance E1. Is the coverage of the models and correlations included in the thermal-hydraulic system code appropriate for analyzing the target passive safety system? [Has the PIRT been prepared and used to evaluate the thermal-hydraulic code? (Are uncertainties of the models and correlations considered to assess the passive safety system performance?)]	**P**
A4. Simultaneous operation of many (multiple trains) systems E1. Has the effect of simultaneous operation of many (multiple trains) passive safety systems been evaluated by the safety analysis?	**O**
A5. Simultaneous operation/optimization of active and passive systems E1. Has the effect of simultaneous operation of the passive safety system and the active system (non-safety system) been evaluated by the safety analysis?	**O**
A6. Reliability E1. Has the reliability model of the passive safety system reflected the root causes derived from functional failure? E2. Has the safety function of the passive safety system been demonstrated by considering all failure modes and any parameters affecting the safety function?	**R**
A7. Evaluation of the effect of malfunction E1. Have the effects of malfunction and inadvertent actuation of the passive safety system been evaluated by the safety analysis?	**O**
A8. Commissioning/Periodic verification tests E1. Not applicable from the safety analysis perspective	**O**
A9. Operability E1. Considering the weak driving force of the passive safety system, is the appropriate check valve model used for the safety analysis?	**P**
A10. Considerations on verification of performance of a passive safety system with weak driving force E1. Has the safety analysis been performed including the effects of non-condensable gas, system leakage, fouling factor of heat exchanger, surface effect (contamination, coating) on condensation, temperature and level of heat sink, initial system configuration (level)? E2. Has the safety analysis been performed considering the effects of atmospheric heat sink (temperature)? E3. Has the safety analysis been performed considering the effects of the aging, such as reducing the diameter of pipes due to contamination? E4. Considering the performance degradation of the passive safety system over time, has the safety analysis been conducted for a sufficiently long time to draw conclusions on the passive safety system performance? E5. Has the safety analysis been demonstrated that there is sufficient margin to avoid cliff-edge effects that may be caused by uncertainties included in the performance evaluation of the passive safety system? (The safety analysis should reflect the uncertainty in the factors that are expected to change in relation to performance and the potential causes of the changes in the factors.)	**P**
A11. Internal and external hazards E1. Has the safety analysis been performed assuming the worst atmospheric heat sink conditions (temperature, humidity and particle concentration) after the accident? E2. Has the safety analysis been performed assuming that the temperature distribution of circulation loop of the passive safety system became the worst condition which impedes natural circulation due to fire? E3. Has the safety analysis been performed assuming that the piping configuration of the passive safety system was deformed by the earthquake and became the worst condition which impedes natural circulation?	**P**
A12. Considerations on human factors E1. Has the safety analysis been performed considering the effect of operator actions (intervention time)?	**O**
A13. Reflection of operating experience E1. Not applicable from the safety analysis perspective	**T**

A14. Considerations on diversity and common cause failure E1. Not applicable from the safety analysis perspective	**O**
A15. Boron effect on natural circulation cooling E1. Has the safety analysis been performed considering flow blockage due to boron precipitation or heat transfer change due to boron coating on surface?	**P**
A16. Debris effect on natural circulation cooling E1. Has the safety analysis been performed considering flow blockage or cooling degradation due to debris?	**P**
A17. Flow instabilities E1. Has the evaluation regarding density wave instability been performed for all operating conditions (including startup) and has the non-existence of undamped oscillation been verified?	**O**
A18. Water/steam hammers phenomena E1. Has the evaluation regarding water hammer phenomena at the startup of the passive safety system been performed and has its impact been verified as negligible?	**O**

※ A: Area; E: Evaluation

Categories: P(Performance); R(Reliability); O(Operability); T(Others)

Table 5 shows consolidated results for evaluation methods for the regulatory focuses on the passive safety system from the present study and the previous study [1]. Note that there are three areas needed to be evaluated not by the safety analysis perspective but by other perspectives. (**A8, A13, A14**)

In addition, there are areas categorized "P" in Table 5. (**A2~A3, A9~A11, A15~A16**) They specially represent items closely related to the performance verification of the passive safety system. Therefore, these must be reflected in the thermal-hydraulic system code analysis when verifying the performance of the passive safety system.

4. Conclusions

The reports published by IAEA SMR regulators' forum [4], and design specific review standards [5] and safety evaluation reports [6] for NuScale reactor published by US NRC are analyzed to identify regulatory practices on the passive safety system.

Then, the identified regulatory practices are consolidated into the previous research result [1] in the form of regulatory focuses on the passive safety system to identify "Comprehensive passive safety system design review focuses". Total 18 design review focuses are identified in the present study.

In addition to that, "Evaluation methods for comprehensive passive safety system design review focuses" are suggested from the safety analysis perspective for the 15 - design review focuses. Further categorization of the 15 focuses shows that there are 7 focuses closely related to performance verification of the passive safety system, which should be reflected in the thermal-hydraulic system code analysis when verifying the performance of the passive safety system.

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- SER 6.3 Emergency Core Cooling System
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- SER 15.9 Stability