REGULATORY RESEARCH ACTIVITY ON SAFETY ANALYSIS METHODOLOGY FOR PASSIVE SAFETY SYSTEMS IN KOREA

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Abstract

Recently, Small Modular Reactors (SMRs) have been actively being developed around the world and many of SMRs adopt passive safety feature as their safety systems. The nuclear industry in Korea is also developing a unique SMR called innovative SMR (i-SMR) fully equipped with Passive Safety Systems. (PSSs) In light of these circumstances, Korea Institute of Nuclear Safety (KINS) has launched a regulatory research project in order to develop a new safety analysis methodology given the PSS characteristics such as weak driving forces leading to a possibility of the functional failure. In the paper, research results achieved so far and future research plan are presented. As for the achievement, the reliability informed regulatory review methodology for safety analyses with PSSs has been developed. First, several potential factors affecting the performance and leading to the functional failure of PSSs are identified. Then, it is shown that the potential factors are able to be incorporated into the REPAS (Reliability Evaluation of Passive Safety System) method as its “the critical parameters”. Next, an exemplary REPAS analysis with a simplified system featuring a PSS is conducted for illustrative purpose. The functional failure rate of the PSS is quantified according to the failure criteria introduced. After that, the REPAS statistical sampling sets highly contributing to the functional failure rate are singled out and they are analyzed to determine specific potential factors needed in-depth regulatory review of their impacts on the safety analysis with the PSSs. Some refinements of the current methodology are suggested for general applications as well. As for the future research plan, PSS issues such as identification of additional failure criteria of the PSS from Failure Mode and Effects Analysis (FMEA) and stable long-term cooling perspectives, a minimum safety margin to avoid the cliff-edge effect, and decision of optimal pre-service/in-service tests conditions as well as newly identified excessive uncertainty issue of thermal-hydraulic system codes are introduced.

1. INTRODUCTION

Currently, SMRs are drawing high attention around the world and in consequence, various type of SMRs such as VOYGR in the US, SMART100 and i-SMR in Korea etc. have been developed or under development. One of common features of those SMRs is introduction of PSSs feature to strengthen safety of the reactors. In light of these circumstance, KINS has recently 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 evaluation methodology for PSSs. This is because PSSs are vulnerable to environmental factors as well as changes of the system configuration due to the intrinsic nature of weak driving force and as a result, the functional failure may happen in spite of complete intactness of the system hardware.

In this paper, we would like to share our research results regarding the reliability informed regulatory review methodology for safety analyses of SMRs featuring PSSs and to introduce ongoing regulatory research program in relation to the PSS in Korea. In section 2, potential factors affecting PSS performance and possibly leading to the functional failure of PSSs are identified through literature review. In section 3, it is shown that the potential factors can be incorporated into the critical parameters of the REPAS method which quantifies the functional failure rate of the PSS. The REPAS method is applied to a simplified system with a PSS for illustrative purpose in section 4. In section 5, the result of the exemplary REPAS application is analysed and specific potential factors needed in-depth regulatory review of their impacts on safety analyses with the PSS are identified through the reliability informed process. In section 6, some further refinements of the present methodology are suggested so that it can be applicable to general applications. In section 7, ongoing research plans regarding PSS issues identified so far are introduced. Finally, the lessons learned from the current study are described in conclusion section.

2. IDENTIFICATION OF POTENTIAL FACTORS AFFECTING PSS PERFORMANCE

Since verifying PSSs design of new reactors is one of critical tasks of nuclear regulators around the world, there have been a lot of efforts to identify the best practices for reviewing PSSs design not only at individual country level but also at international level and as a result, these efforts lead to several publications. First off, we analysed some of those publications such as Korean regulatory guide on PSS design [1] as individual country level reference, and the reports from OECD/NEA Regulation of New Reactors Working Group (WGRNR), WENRA Reactor Harmonization Working Group (RHWG) and IAEA SMR Regulator Forum [2-4] as international level references to draw comprehensive design review items on PSSs and then finally extracted potential factors affecting the PSS performance and potentially leading to the functional failure from the comprehensive design review items. [5] The result is summarized into Table 1 below. Note that the potential factors in Table 1 are chosen because they can lead to different performance simulation results for PSSs by thermal-hydraulic codes. Also note that US NRC design specific review standards for the NuScale reactor [6] and its safety evaluation reports [7] were reviewed and incorporated into the Table 1 as items No. 10 and 11.

TABLE 1. The Potential Factors Affecting the PSS Performance

No.	Potential Factors Affecting PSS Performance	Note
1	Models and Correlations Uncertainties of Thermal-Hydraulic Code	**Heat Transfer Model**, Check Valve Model, etc.
2	Non-condensable Gas Concentration	
3	Leakage of Working Fluid	
4	Fouling Factor of Heat Exchanger	
5	Surface Effect on Condensation	Surface Contamination/Coating
6	Fluid Conditions of Heat Sink (Cooling Tank)	**Temperature**, Level
7	Initial System Configuration	Initial Inventory of PSS when it starts to operate
8	Aging Effect	**Reduction in Pipe Diameter**
9	Accident/Hazard Effect	• Containment Atmosphere Conditions* Change (by Accident) • Temperature Distribution Along Circulation Loop (by Fire) • Piping Slope Change (By Earthquake)
10	Boron Effect	• Flow Blockage due to Boron Precipitation • Heat Transfer Change due to Boron Coating on Heat Transfer Surface
11	Debris Effect	• Flow Blockage due to Debris • Heat Transfer Change due to Debris Coating on Heat Transfer Surface

Note: Containment Atmosphere Conditions* mean **temperature (heat loss from PSS)**, humidity and particle concentration.

3. INCORPORATION INTO THE REPAS METHOD

The REPAS is a reliability evaluation method for PSSs developed in late 1990s based on uncertainty propagations of design and critical parameters. [8,9] It can be used to quantify the functional failure rate of a PSS when the functional failure is connected with the occurrence of thermal-hydraulic phenomena. In the REPAS method, by definitions [8], design parameters and critical parameters are classified as: the design parameters-those parameters coming from the connection between the passive system and the complete system into which the passive system is inserted and by which the passive system is affected, and the critical parameters-passive system parameters which identify the passive system behaviour, taken as indicators for the system failure causes or joint causes.(In other sense, the critical parameters refer items that could lead to a performance degradation of the passive system, namely affecting the heat transfer capability and the natural circulation flow rate. [8])

Since the potential factors from Table 1 were identified as affecting the PSS performance, and if we recall the definition of the critical parameter of the REPAS method, the potential factors from Table 1 can be taken as "the critical parameters" when the REPAS method is applied. Since one of the general objectives of the REPAS is in an analytical way to characterize the performance of a PSS in order to increase the confidence toward its operation [9], it is clear that we can investigate the PSS performance degradation due to the potential factors through the application of the REPAS while adopting the potential factors in Table 1. as the critical parameters. In the following sections, an illustrative application of the REPAS to a simplified system (Section 4) and a development of the reliability informed regulatory review methodology for the PSS based on the result of the illustrative application are explained in detail. (Section 5)

4. AN EXEMPLARY APPLICATION OF THE REPAS METHOD FOR A SIMPLIFIED SYSTEM

In the present section, an exemplary application of the REPAS method is conducted by incorporating a limited number of critical parameters from Table 1 (See, the 4 red items in Table 1) and a design parameter for a simplified system. [10] The simplified system employed here for the REPAS application mimics a situation where residual heat of a reactor is removed by a Passive Residual Heat Removal System (PRHRS).

4.1. Development of the simplified system and its operating scenario

The simplified system used in the present study is depicted in Fig. 1. The system is comprised of a Primary Tank (PT) with a heater to mimic a reactor core and the PRHRS with a Cooling Tank (CT), a heat exchanger bundle, and connecting pipes. The cooling tank was modelled with 500 m^3 and 6.5 m of liquid volume and liquid height, respectively. The heat exchanger bundle consisted of 20 tubes with 1 cm of inner diameter and 1 m of effective heat transfer length each. The primary tank was modelled with 4.78 MPa of initial pressure and 0.5 MW of initial thermal power. The thermal power was modelled to decrease over time. The heat exchanger bundle and the primary tank were connected by pipes with 50 mm of diameter and 40 m long. Activation of the PRHRS is assumed as follows. Water level of the primary tank starts to decrease by opening a pressure boundary isolation valve. When the water level of the primary tank reaches 3.6 m, the pressure boundary isolation valve is closed immediately and the PRHRS actuation valves are opened. As a result, steam flow enters the heat exchanger bundle and due to the heat transfer from the heat exchanger bundle to the cooling tank, the steam condenses and the primary tank pressure starts to decrease.

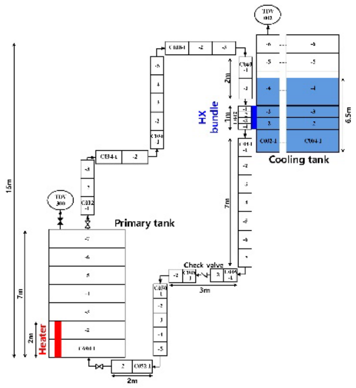


FIG. 1. Conceptual Design and Input Node Diagram of the Simplified System. [10]

4.2. Selection of the parameters and the functional failure criteria

In the present study, only limited number of design and critical parameters were used for illustrative purpose of the REPAS method. Table 2 shows the selection of the design and the critical parameters, and their probability distributions assumed for the REPAS application.

TABLE 2. Selected Design and Critical Parameters, and Their Probability Distributions [10]

Parameters		**Nominal Value**	**Probability Distribution**			
Design	Initial Pressure of PT (P_{PT})	4.78 MPa	Discrete			
			Value	4.78MPa	5.78MPa	6.78MPa
			Probability	0.85	0.1	0.05
Critical	Uncertainty of Heat Transfer Model (U)	0.0%	Normal (μ:0.0, σ:0.5)			
	Initial Temperature of CT (T_{CT})	298.15K	Normal (μ:298.15, σ:5.0)			
	Flow Area (A_{pipe})	0.002027m^2 (100%)	Discrete			
			Value	90%	95%	100%
			Probability	0.03	0.07	0.9
	Heat Transfer Coefficient for Heat Loss (H_{Loss})	2.0 W/m^2K	Discrete			
			Value	2.0W/m^2K	10.0W/m^2K	20.0W/m^2K
			Probability	0.7	0.2	0.1

Since the Functional Failure Criteria (FFC) should be defined to evaluate the reliability of the PSS in the REPAS method, two FFCs are devised in the present study. Since the main function of the PRHRS is to depressurize the PT by two phase heat transfer between the CT and the PT, we choose the depressurization time at the PT and the ratio of heat between the CT and the PT as the FFCs of the PRHRS. Two functional failure criteria are given as below.

- FFC_1: Depressurization time

$$FFC_1 = \tau\ (at\ P_{PT} = 1.0MPa) > 2000s \quad (1)$$

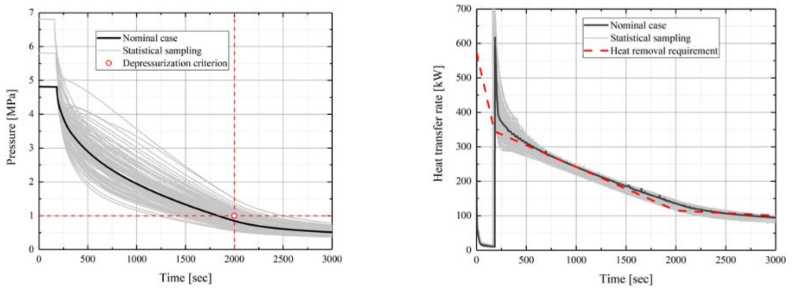
- FFC_2: Ratio of total removed heat by the CT to total generated heat by the PT

$$FFC_2 = \frac{\int_{t=0s}^{t=2000s} \dot{Q}_{CT} dt}{\int_{t=0s}^{t=2000s} \dot{Q}_{PT} dt} < 1.15 \quad (2)$$

where $\dot{Q}_{CT}$: Heat transfer rate of heat exchanger bundle in the CT and $\dot{Q}_{PT}$: Heat transfer rate of the PT.

4.3. Deterministic evaluation of the nominal case and the statistical sets

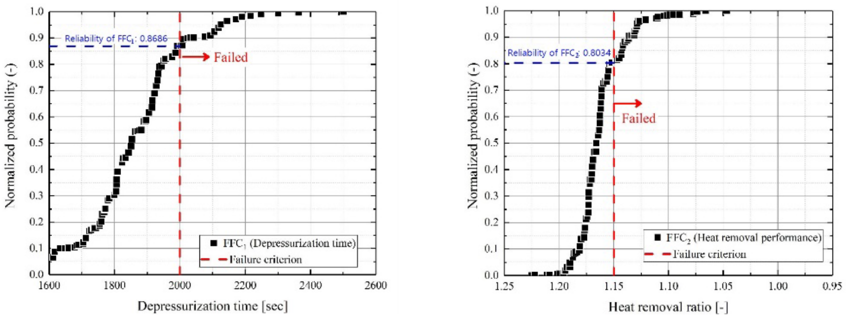
The REPAS parameters (design and critical), and their nominal values and probability distributions having been decided, deterministic evaluation of the simplified system behaviour is conducted for nominal case and the statistical sets. In the present study, the MARS-KS code [11] is used for thermal-hydraulic calculation and Latin Hypercube Sampling (LHS) is applied to produce 100 statistical sets by DAKOTA program [12] for the statistical sampling of the design and critical parameters. The simulation results for both of pressure and heat removal rate at the cooling tank are shown in Fig. 2. As for the nominal case, the pressure of the primary tank is decreasing up to 1.0 MPa at 1833 sec and the ratio of total removed heat by the cooling tank to total generated heat by the primary tank up to 2000 sec is calculated to 1.17. Therefore, both of FFCs are not met for the nominal case. However, Fig. 2 also shows that the functional failure criteria are met for some statistical sets. Specifically, there are 20 and 40 cases which do meet the functional failure condition FFC_1 and for FFC_2, respectively.



(a) Pressure of PT (b) Heat Transfer Rate of PT and CT

FIG 2. MARS-KS Statistical Sets Simulation Results of the PRHRS. [10]

By counting the statistical sets which do not meet the functional failure criteria, individual reliabilities of the PRHRS for the assumed scenario with respect to FFC_1 and FFC_2 were quantified as 0.8686 and 0.8034, respectively. The combined reliability with respect to FFC_1 and FFC_2 is also calculated as 0.7734. Fig. 3 shows the cumulative probability of the functional failure criteria and resulting reliabilities.



(a) FFC_1 (b) FFC_2

FIG. 3. Cumulative Probability of Functional Failure Criteria. [10]

5. THE RELIABILITY INFORMED REGULATORY REVIEW METHODOLOGY FOR SAFETY ANALYSES WITH PASSIVE SAFETY SYSTEMS

Table 3 shows information of the design and critical parameters values and the calculation result with respect to each of the functional failure criteria, FFC_1 and FFC_2 for some statistical sets out of 100 samples. [10] The Combined Functional Failure Criterion, CFFC is also shown in the table. The combined functional failure criterion is set to "Y" when any of FFC_1 or FFC_2 are flagged "Y". Note that the summation of occurrence probabilities of all statistical sets where the CFFC is flagged by "N" can be considered as a reliability of the PRHRS with respect to CFFC.

TABLE 3. Sampling of Statistical Sets and Their Calculation for Functional Failure Criteria [10]

Set No.	T_{CT}	U	P_{PT}	H_{Loss}	A_{pipe}	Occurrence Probability	FFC_1		FFC_2		CFFC	Note
0	298.15	0.0	4.78	2	100	2.830E-06	1833.0	N	1.1700	N	N	Reference
1	304.3	6.1	4.78	10	100	3.795E-07	1943.9	N	1.1108	Y	**Y**	
2	303.3	6.9	4.78	10	100	4.523E-07	1956.2	N	1.1093	Y	**Y**	
3	297.8	1.5	4.78	10	100	9.608E-07	1759.8	N	1.1293	Y	**Y**	
9	302.6	8.8	4.78	2	100	1.555E-06	2105.9	Y	1.1438	Y	**Y**	2nd
10	291.4	8	5.78	2	100	1.175E-07	2003.1	Y	1.1731	N	**Y**	
…	…	…	…	…	…	…	…	…	…	…	…	…
40	292.8	-12.5	5.78	2	100	1.036E-07	1559.4	N	1.2085	N	N	
41	298.4	8.3	4.78	2	100	2.409E-06	2010.1	Y	1.1535	N	**Y**	1st
42	298.1	-11.7	4.78	2	100	1.723E-06	1580.9	N	1.1899	N	N	
…	…	…	…	…	…	…	…	…	…	…	…	…
73	306.6	2.3	4.78	2	100	7.968E-07	1973.1	N	1.1576	N	N	
74	296.5	12.7	4.78	2	100	1.438E-06	2118.7	Y	1.1427	Y	**Y**	3rd
75	295.8	13	4.78	2	100	1.318E-06	2125.8	Y	1.1419	Y	**Y**	5th
…	…	…	…	…	…	…	…	…	…	…	…	…
95	302.4	10.3	4.78	2	100	1.398E-06	2144.7	Y	1.1402	Y	**Y**	4th
96	298.7	17	4.78	2	100	7.934E-07	2249.1	Y	1.1307	Y	**Y**	
100	302.8	0.8	4.78	2	100	2.205E-06	1932.5	N	1.1615	N	N	

Table 3 also shows the top 5 statistical sets (in yellow) from the occurrence probability point of view while having the CFFC flagged "Y". In other word, these are the top 5 statistical sets contributing most to the functional failure of the PRHRS with respect to the combined functional failure criterion. If we look into those 5 statistical sets, it is clear that two critical parameters such as the uncertainty of heat transfer model (U) of the thermal-hydraulic code and the initial temperature of the cooling tank (T_{CT}) are the most impactful parameters to the functional failure of the PRHRS because the other three parameters including one design parameter remain the same as their nominal values. Therefore, the present exemplary application clearly shows that specific identification of some potential factors to increase the reliability of the PRHRS (in other term, to decrease the functional failure rate of the PRHRS) is possible through the REPAS method. Since existing non-LOCA safety analysis only takes care of initial conditions such as 1) reactor power, 2) reactor coolant system temperature 3) reactor coolant system flow 4) pressurizer pressure 5) pressurizer level etc. to guarantee a conservative safety analysis, the prioritized critical parameters identified by the reliability informed process in the present study should be additionally taken into account during a regulatory review on safety analyses with PSSs to avoid any possibility of functional failures of PSSs. We suggest this procedure as "the reliability informed regulatory review methodology for safety analyses with PSSs".

6. NOTES FOR GENERAL APPLICATION OF THE PRESENT METHOD

Although the exemplary application of the REPAS to the simplified system shows how the present method can be implemented, there are some points need to consider in order to apply the current methodology to a plant application with realistic manner.

- Although there is only one "design parameter (initial pressure of the primary tank, P_{PT})" employed in the exemplary application, there must be several other design parameters for a real plant application. It seems to be reasonable to assume the thermal-hydraulic variables from conservative initial conditions of the NSSS (Nuclear Steam Supply System) for Non-LOCA safety analysis as the relevant design parameters.

- Since there are a limited number of “critical parameters used in the exemplary application, the prioritization of critical parameters was direct and intuitive. However, if we employ all conceivable critical parameters from Table 1 for a real plant application, the prioritization with direct and intuitive manner may not be applicable. In such case, we recommend a correlation analysis between a functional failure criterion and each of critical parameter for statistical sets meeting the relevant functional failure criteria to identify the most impactful/contributing critical parameter to each functional failure criterion.
- In the exemplary application, the probability distribution of each critical and design parameter was assumed roughly. However, each probability distribution of each parameter should be precise and reasonable as much as possible for a realistic plant application. For example, a recent international research project, PERSEO [13] shows that condensation heat transfer models in thermal-hydraulic codes have much uncertainty than previously thoughted. This finding should be implemented in applying the current methodology.

7. ONGOING RESEARCH ITEMS REGARDING PASSIVE SAFETY SYSTEMS

As the second phase of the regulatory research program (2024-2026) regarding PSSs, several research about PSSs is going on in Korea. Some major research topics in progress are summarized as below.

- Although two FFCs were introduced in the exemplary application, there still exist some possibilities to consider other FFCs to guarantee a sound operation of a PSS because the vulnerability of PSS for its safe operation is relatively high. In this respect, Failure Mode and Effect Analysis (FMEA) of PSSs may be a good reference to review to identify additional FFCs. By the way, a driving force of a PSS is diminishing and long-term cooling capability of the PSS becomes weak as time goes on. As a result, the PSS function might be disrupted or turned into unstable. From these recognitions, we are looking for FFCs of PSSs from FMEA and from stable long-term PSSs operation perspectives.
- In the present study, the effect of potential factors on functional failure of PSSs is focused and the new methodology is developed to incorporate the specific potential factors on the safety analysis with PSSs. However, even though the present methodology would be successfully applied to, there is a possibility that the PSS may still experience the cliff-edge effect. This is because the driving force or cooling flow calculation of PSSs by a Thermal-Hydraulic (TH) code would have bigger uncertainty compared to those of Active Safety Systems (ASSs) and this uncertainty together with the other uncertainties of the TH code may hide the cliff edge effect in a real-world PSS. Therefore, in order to avoid this cliff-edge effect and keep the decent level of safety, the safety analysis margin of a PSS should be maintained bigger than that of an equivalent ASS. In this respect, we are addressing a minimum required safety margin issue of PSSs.
- It's an issue for a SMR adopting PSSs how to ensure its PSS operability at its design condition by the pre-service or in-service tests. This is because it is difficult to realize a real test condition close to the design condition of the PSS and a PSS heat removal is determined in a passive manner by an applied heat generation. To overcome this intrinsic difficulty and to find a best available method to demonstrate a PSS operability, we are doing research to find a specific initial condition or a test configuration for the pre-service or in-service tests. The initial condition or test configuration of the PSS test should be not only actually feasible but also giving the lowest reliability with the REPAS method having the potential factors on functional failure of PSSs. That is to say, by demonstrating the operability of a PSS through the specifically determined pre-service or in-service test condition or configuration with the lowest reliability, we might have higher confidence in a real PSS operability.
- Recently, PERSEO, the international research project on a passive system organized by OECD/NEA [13] has identified a new challenge. Through the PERSEO, it has been discovered that many existing TH system codes used to analyse passive systems fail to simulate a benchmark experiment of the PERSEO without artificial adjustment of condensation heat transfer model

coefficient. On this finding, the separate and independent a TH code evaluation (for MARS-KS code) is under way. Depending this research result, the MARS-KS code uncertainty level may need to be adjusted when the REPAS method is applied.

8. CONCLUSIONS

The regulatory research activities on passive safety systems is actively underway in Korea in conjunction with Korean nuclear industry effort to develop small modular reactors having passive safety features. Korea Institute of Nuclear Safety has launched the regulatory research program since 2021 and successfully developed the reliability informed regulatory review methodology for safety analyses with passive safety systems by combining the potential factors degrading passive safety systems performance with the REPAS method. In case of a submission of standard design certificate application on i-SMR, the present method will be applied to regulatory review on safety analyses with PSSs.

Some technical challenges of passive safety systems such as identification of additional failure criteria of the PSS from FMEA and stable long-term cooling perspectives, a minimum safety margin to avoid the cliff-edge effect, and decision of optimal pre-service/in-service tests conditions as well as the resolution of the excessive uncertainty issue of thermal-hydraulic system codes are also being actively studied these days. We hope the information presented in this paper could help the nuclear society including regulatory bodies and industry around the world to ensure the safety of small modular reactors featuring passive safety systems.

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REFERENCES

[1] Korea Institute of Nuclear Safety (KINS), Regulatory Guide on Design of Passive Safety System, KINS/RG-N07.12, KINS, Daejeon, Korea (2021).

[2] OECD/NEA, Survey on the Regulatory Practice to Assess Passive Safety Systems Used in New Nuclear Power Plant Designs, NEA/CNRA/R(2017), Working Group on Regulation of New Reactors, France (2017).

[3] WENRA, Regulatory Aspects of Passive System, Reactor Harmonization Working Group, EU (2018).

[4] IAEA, Phase 2 Report, Small Modular Reactors Regulators' Forum Working Group on Design and Safety Analysis, Austria (2021).

[5] PARK, J. Y. and LEE, S. H., "Areas of Regulatory Review Focuses on Passive Safety System Design," Transactions of the Korean Nuclear Society Autumn Meeting, Changwon, Korea, October 20-21 (2022).

[6] US NRC, Design-Specific Review Standard (DSRS) for NuScale SMR Design, DSRS 5.4.7, DSRS BTP 5-4, DSRS 6.2.2, DSRS 6.3, DSRS 15.6.6, DSRS 15.9.A, US NRC, the US (2016).

[7] US NRC, Safety Evaluation Report (SER) for NuScale Reactor, SER 5.4.4, SER 6.2.2, SER 6.3, SER 15.6.6, SER 15.9, US NRC, the US (2020).

[8] RICOTTI, M. E., BIANCHI, F., BURGAZZI, L., D'AURIA, F., and GALASSI, G., "The REPAS Study: Reliability Evaluation of Passive Safety Systems," Proceedings of 10th International Conference on Nuclear Engineering (ICONE10), Arlington, Virginia, the US, April 14-18 (2002).

[9] JAFARI, J., D'AURIA, F., KAZEMINEJAD, H., and DAVILU, H., "Reliability evaluation of a natural circulation system," Nucl. Eng. Des. 224, pp. 79-104 (2003).

[10] JEON, S. S., LEE, J. H., et al., "System Code Analysis for Reliability Evaluation of Passive Safety System," NSTAR-22NS22-194, Korea Foundation of Nuclear Safety.

[11] Korea Institute of Nuclear Safety (KINS), MARS-KS Code Manual, Volume V: Models and Correlations Manual, KINS/RR-1822, Vol. 5, KINS, Daejeon, Korea (2022).

[12] "DAKOTA manual," https://Dakota.sandia.gove/sites/default/files/docs/6.17.0-release/user-html/ (2022).

[13] MASCARI, F. et al., "OECD/NEA/CSNI/WGAMA PERSEO benchmark: Main outcomes and conclusions," Nucl. Eng. Des. 405, 112220 (2023).