

Thermal-Hydraulic Analysis-Based Reliability Assessment of Passive Safety Systems for i-SMR

Inseo Nam ^a, Gangmin Kim ^a, Jin Hee Park ^b, Sung Min Shin ^b, Jaehyun Cho ^{a*}

^aChung-Ang Univ., 84 Heukseok-ro, Dongjak-gu Seoul 06974, Republic of Korea

^bKorea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon, 34057, Republic of Korea

*Corresponding author: jcho@cau.ac.kr

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1. Introduction

In recent reactor designs, passive safety systems have been increasingly employed in response to the growing emphasis on enhanced nuclear safety. According to the IAEA definition [1], a passive safety system refers to a system that performs its safety function without reliance on external power, instead relying on natural laws, material properties, and internally stored energy.

Passive safety systems have been increasingly adopted in advanced reactor designs owing to their potential to enhance reactor safety. Nevertheless, their performance is inherently affected by the physical conditions and uncertainties associated with the underlying natural phenomena. Consequently, a passive safety system may fail to provide the required safety function even in the absence of mechanical component failures, resulting in functional failure. Therefore, an appropriate reliability assessment methodology that accounts for functional failure is important.

This study quantifies the functional failure probability of the Passive Auxiliary Feedwater System (PAFS) in the i-SMR under Loss Of Main Feedwater (LOMF) scenario. Key thermal-hydraulic parameters affecting the system performance are selected as uncertain parameters and randomly sampled using MOSAIQUE according to their prescribed probability distributions or uncertainty ranges. The sampled parameters are incorporated into the MARS-KS input model, and 210 thermal-hydraulic simulations are performed for the LOMF scenario. The resulting thermal-hydraulic responses are then used to estimate the functional failure probability of the PAFS.

2. Methods and Results

The reliability assessment of the passive safety system was performed according to the following steps.

- Nominal case analysis
- Define failure criteria
- Relevant parameter selection
- Random sampling and TH code analysis
- Reliability estimation

2.1. Nominal case analysis

To establish reference thermal-hydraulic behaviors of i-SMR Passive safety systems under the LOMF scenario, nominal case analysis was performed. The system response was simulated using MARS-KS TH system analysis code at Nominal condition of physical parameters. In the LOMF scenario, the loss of main feedwater leads to the closure of the Main Feedwater Isolation Valves (MFIV), while the Passive Auxiliary Feedwater Isolation Valves (PAFIV) open to initiate decay heat removal through the PAFS. In this study, the accident is assumed to be mitigated solely by the PAFS, without considering the intervention of other safety systems. At the early stage of the transient, a rapid increase in the primary system pressure causes the Pressurizer Safety Relief Valves (PSRV) to open temporarily. Subsequently, continuous heat removal by the PAFS stabilizes the system pressure and maintains core integrity throughout the transient [2].

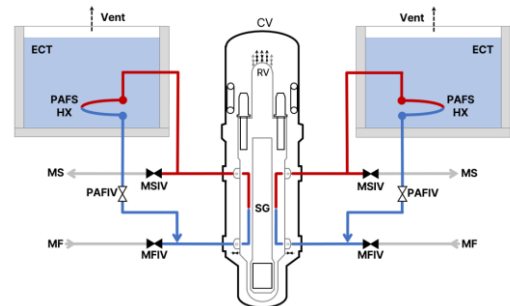


Fig. 1. Schematic diagram of i-SMR passive safety systems

2.2. Define failure criteria

Even when a passive safety system is successfully actuated, functional failure may still occur if the system does not adequately perform its intended safety function. Therefore, failure criteria need to be defined to identify functional failure. It may be defined using system-specific performance parameters, such as the heat removal rate or system flow rate. However, system-specific failure criteria can be difficult to define objectively because the selection of appropriate threshold values may involve considerable ambiguity. Thus, this study adopts global failure criteria based on plant-level safety parameters [3]. Functional failure of the i-SMR passive safety systems is defined as a maximum Containment Vessel (CV) pressure

exceeding 50 bar which is design pressure or a peak cladding temperature (PCT) exceeding 1477 K.

2.3. Relevant parameter selection

The physical parameters that may affect the functional failure of the passive safety system were identified, and an uncertainty range and probability distribution were assigned to each parameter. The process for identifying the key relevant parameters should be clearly defined, and no potentially important parameter should be omitted. Therefore, the factors affecting the performance of the passive safety system were classified into four categories as shown in Fig.2, and the relevant parameters associated with each category were identified.

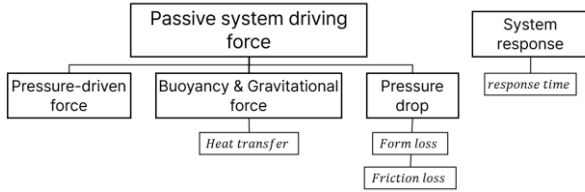


Fig. 2. Classification of factors affecting passive safety system performance

Buoyancy and gravitational forces include the driving forces generated by heat sources and heat sinks, and parameters related to heat transfer were considered accordingly. Pressure-driven force represents the driving force induced by a pressure difference, and parameters associated with pressure drop, such as form loss and friction loss, were also taken into account. Finally, the effect of the system response time on the system performance was considered. Based on this classification, a total of 20 relevant parameters were identified, as summarized in table 1.

Table I: List of relevant parameters

	Category	Description	distributi on	Range
1	Buoyancy & gravitational force	Po	Operational Power	Normal ±10 MW
2		kk_RV	Conductivity of RV	Normal ±10%
3		k_c	Conductivity of Cladding	Normal ±10%
4		kk_S	Conductivity of SG	Normal ±10%
5		kk_Hx	Conductivity of PAFS Hx	Normal ±10%
6		A_S	SG Surface Area	Normal ±5%
7		A_Hx	PAFS Hx Surface Area	Normal ±5%
8		th_S	SG Thickness	Normal ±4%
9		th_Hx	PAFS Hx Thickness	Normal ±4%
10		h_S	HTC of SG	Normal ±20%

11		h_Hx	HTC of PAFS Hx	Normal	±20%
12		T_E	Pool Initial Temperature	Normal	±10–20 K
13	Pressure-driven force	P_R	Pressurizer Initial Pressure	Normal	±0.2 MPa
14	Pressure drop	K_R	RV Form-Loss Coefficient	Uniform	±50%
15		K_S	SG Form-Loss Coefficient	Uniform	±50%
16		K_P_in	PAFS inlet Form-Loss Coefficient	Uniform	±50%
17		K_P_Hx	PAFS Hx Form-Loss Coefficient	Uniform	±50%
18		A_V	PAFIV Valve Area	Normal	±4%
19	system response	t_R	Scram Delay Time	Uniform	+10 sec
20		t_P	PAFIV Open Delay Time	Uniform	+10 sec

2.4. Random sampling and TH code analysis

The 20 relevant parameters were randomly sampled according to their prescribed uncertainty ranges and probability distributions by MOSAIQUE, and a total of 210 thermal-hydraulic analyses were performed using MARS-KS.

As shown in Fig.3, during the early stage of the accident, an increase in the Reactor Vessel (RV) pressure causes the PSRV to open, resulting in an increase in the CV pressure. Subsequently, heat removal through the PAFS leads to depressurization of the RV, while the CV pressure also gradually decreases.

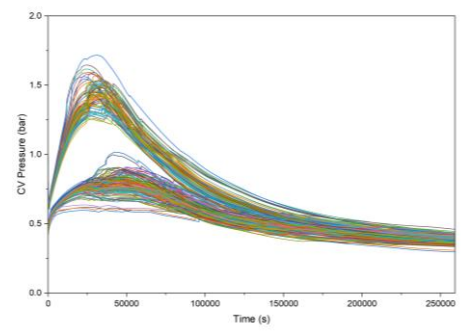


Fig. 3. CV pressure plot for LOMF scenario obtained from the 210 TH analysis cases

As shown in Fig. 4, the maximum PCT remains within a narrow range of 633–638 K for all cases. This is because, despite the coolant discharge caused by PSRV opening, the coolant level does not decrease sufficiently to uncover the core in any of the cases. While, Fig.5 shows that the maximum CV pressure exhibits two distinct groups, one below 1 bar and the other above 1.2 bar. This behavior appears to be primarily governed by the number of PSRV actuations: the PSRV opens once in 144 cases and twice in 66 cases, indicating that the

total number of PSRV openings has a dominant influence on the peak CV pressure.

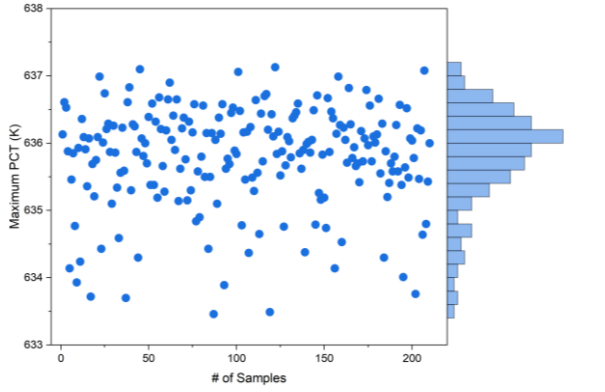


Fig. 4. Distribution of maximum PCT obtained from the 210 TH analysis cases

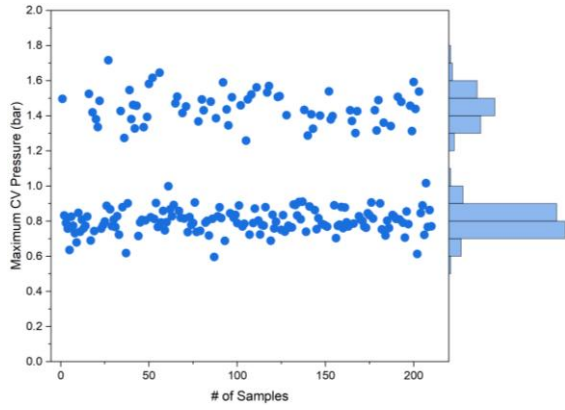


Fig. 5. Distribution of maximum CV pressure obtained from the 210 TH analysis cases

In addition, a sensitivity analysis was performed to identify which of the 20 relevant parameters had the most dominant influence on the functional failure of the system. Since the CV pressure exhibited a relatively large variation among the analyzed cases, the 20 relevant parameters and the CV pressure were standardized, and the Standardized Regression Coefficient (SRC) analysis was subsequently performed. SRC analysis quantifies the relative influence of each input parameter on the output response. The sign of the SRC indicates the direction of the influence, while its absolute magnitude represents the relative importance of the corresponding parameter.

Among the 20 relevant parameters, the scram delay (t_R) exhibited the largest SRC value of 0.89001, indicating a dominant influence on the CV pressure. As the scram delay increases, the RV pressure continues to rise for a longer period, which consequently affects the number of PSRV actuations. Based on the SRC analysis, the scram delay was therefore identified as the most influential parameter among the 20 relevant parameters

and should be given particular consideration in the reliability assessment of the passive safety system.

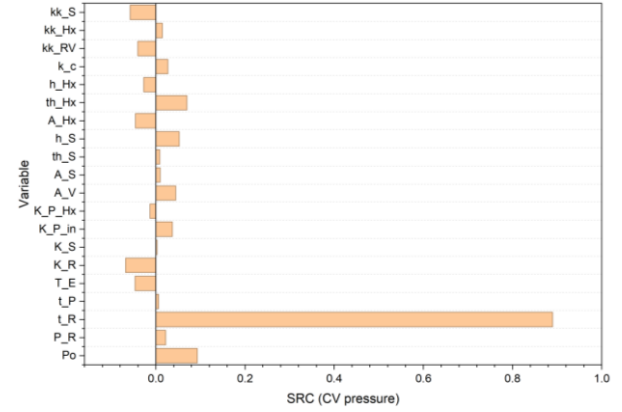


Fig. 6. SRC analysis results for 20 relevant parameters (CV pressure)

2.5. Reliability estimation

Based on the TH code analysis results, the probability of exceeding the failure criterion was estimated. The exceedance probability was evaluated only for the CV pressure, rather than for the PCT, which exhibited only a narrow range of variation. As shown in Fig. 7, normal, lognormal, and gamma distributions were fitted to the CV pressure data obtained from the 210 analysis cases, and the exceedance probability, $P(\text{CV pressure} > 50 \text{ bar})$, was calculated for each fitted distribution. Among the considered distributions, the lognormal distribution yielded the highest exceedance probability, with $P(\text{CV pressure} > 50 \text{ bar}) = 1.575\text{E-}43$. This result indicates that the probability of functional failure exceeding the CV pressure limit is extremely low under the analyzed conditions.

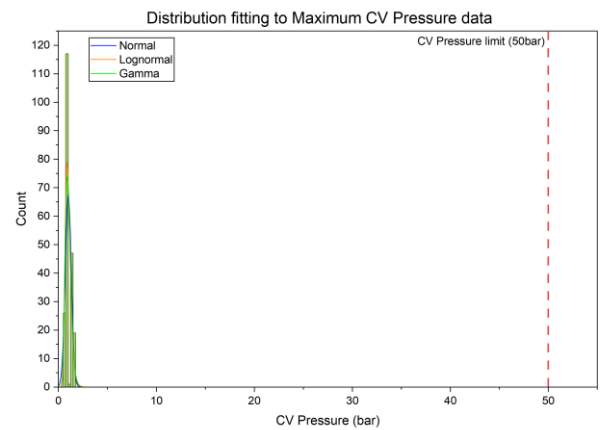


Fig. 7. Normal, lognormal, gamma distribution fitting to maximum CV pressure data

In addition, non-informative prior distributions were specified as

$$p(\mu_{log}, \sigma_{log}) \propto \frac{1}{\sigma_{log}} \quad (1)$$

for the parameters of the lognormal distribution, and were subsequently updated using Bayesian inference

$$p(\mu_{log}, \sigma_{log} | D) = \frac{p(D | \mu_{log}, \sigma_{log})p(\mu_{log}, \sigma_{log})}{p(D)} \quad (2)$$

to obtain posterior distribution. Using the obtained posterior distribution, the exceedance probability was further evaluated under a more conservative assumption, as expressed in Equation.

$$P(CV \text{ pressure} > 50bar | D) = \int p(CV \text{ pressure} > 50bar | \mu_{log}, \sigma_{log}) \cdot p(\mu_{log}, \sigma_{log} | D) d\mu_{log} d\sigma_{log} \quad (3)$$

The resulting probability was evaluated as $P(CV \text{ pressure} > 50 \text{ bar}) = 2.865E-31$, which still indicates an extremely low probability.

3. Conclusions

In this study, to assess the reliability of the i-SMR passive safety systems under the LOMF scenario, a nominal-case thermal-hydraulic analysis was performed using MARS-KS and the failure criteria were defined as (CV pressure > 50bar) or (PCT > 1477K). 20 relevant parameters with the potential to affect the functional failure of the system were systematically identified, and an uncertainty range and probability distribution were assigned to each parameter. Subsequently, 210 input files were generated using MOSAIQUE by randomly sampling the 20 relevant parameters according to their assigned uncertainty ranges and probability distributions, and corresponding thermal-hydraulic analyses were performed using MARS-KS.

The analysis results showed that the PCT remained within a narrow range of 633–638 K for all cases, as the core remained covered throughout the transient. In addition, the CV pressure remained below 2 bar in all cases. These results indicate that substantial safety margins were maintained with respect to both failure criteria.

Normal, lognormal, and gamma distributions were fitted to the CV pressure data obtained from the 210 analysis cases. A conservative estimate of the probability of exceeding the failure criterion was further obtained by incorporating non-informative priors and performing Bayesian updating. The resulting exceedance probability was found to be extremely low, indicating a very high reliability of the i-SMR passive safety systems under the LOMF situation.

ACKNOWLEDGEMENT

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