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Conceptual Study for Reliability Evaluation of Passive Residual Heat Removal System

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1. Introduction

The various Passive Safety Systems (PSS) (such as Passive Residual Heat Removal System (PRHRS) [1,2], Passive Containment Cooling System (PCCS) [3], Passive Auxiliary Feedwater System (PAFS) [3], and Passive Safety Injection System (PSIS) [2]) have been widely developed for advanced light water reactor (ALWR) through that was considered to ensure the higher reliability and safety than active safety system due to its low dependency on the operator and external power source.

However, it is difficult to prove the performance and reliability of the PSS under various operational or environmental conditions due to the less driving force of natural circulation (e.g., density difference of working fluid, pressure difference, gravity, etc.) than forced convection.

From 2002, Coordinated Research Project (CRP) was conducted by IAEA [4,5] to establish the methodology for reliability and performance evaluation of PSS. Through the CRP, numerous reliability evaluation methodologies were compared and major issues for PSS were also discussed.

To evaluate the reliability of PSS, functional failure approach is additionally required with classical reliability evaluation approach, such as independent failure modes approach and hardware failure modes approach [6]. Functional failure of PSS can be defined that current performance (capacity) of PSS under various operation/design condition due to uncertainty of parameters and environmental condition is less than required performance (load), even if PSS is operated. Therefore, functional failure approach should be considered to evaluate the reliability of PSS.

In this study, conceptual study for reliability evaluation was conducted by preliminary application of reliability evaluation methodology to conceptual design of Passive Residual Heat Removal System (PRHRS). Reliability evaluation was conducted through DAKOTA (uncertainty quantification program developed by Sandia National Laboratory) and MARS-KS code (best-estimated thermal-hydraulic analysis code developed by Korea Institute of Nuclear Safety) for parameter sampling and thermal hydraulic analysis, respectively.

2. Reliability Evaluation Methodology

For the reliability evaluation of PSS, RMPS (Reliability Method for Passive Safety functions) framework [7] and APSRA$^+$ (Analysis of Passive System ReliAbility Plus) framework [8] were representative methodologies. RMPS improved from REPAS (Reliability Evaluation of Passive Safety Systems) is a reliability evaluation framework for PSS developed by EU based on uncertainty propagation of physical/design parameters. And also, APSRA$^+$ is a framework for reliability evaluation of PSS which was developed based on failure surface of deviations on parameters decided by fault tree analysis. REPAS (or RMPS) and APSRA$^+$ have certain features in common, as follows [9].

- Thermal-hydraulic analysis by best-estimate code is required to find PSS performance and influence of sensitive parameters.
- Thermal-hydraulic failure criteria of the PSS are defined.
- Probabilistic and deterministic tools are used to assess the reliability of PSS.

On the other hand, both methodologies also have differences in certain aspects, as follows [9].

- Probability density function (PDF) was used to decide the variation of parameters in REPAS. However, parameter variation in APSRA$^+$ is treated by root diagnosis.
- For the uncertainty of model, REPAS and APSRA$^+$ used PDF and experimental validation, respectively.
- For reliability evaluation, REPAS adopted Monte-Carlo evaluation while APSRA$^+$ adopted the failure surface prediction and fault tree analysis.

In this study, reliability evaluation methodology based on the REPAS was applied to assess the reliability of PRHRS on the change or uncertainty of design/operation parameters, because REPAS is essential process for RMPS. In terms of conceptual study, distribution of design/operation parameters and failure criteria used in this study were decided by engineering judgment, which was selected by considering of sufficiently effect of sensitivity of parameters on the PRHRS performance.

3. Passive Safety System

In this section, selected conceptual design of PRHRS for reliability evaluation was described. And also, thermal hydraulic behavior during accident scenario was analyzed by MARS-KS code.

3.1 Conceptual Design of Passive Residual Heat Removal System

Passive Residual Heat Removal System (PRHRS) was selected as a Passive Safety System (PSS) to apply reliability evaluation methodology.

Conceptual design of PRHRS for small modular reactor was depicted in Fig. 1. PRHRS consisted of Steam generator, cooling tank including heat exchanger bundle, and connected pipes. Cooling tank was modeled by 500 m^3 and 6.5 m of liquid volume and liquid height, respectively. Heat exchanger bundle consisted of 20 tubes with 1 cm of inner diameter and 1 m of heat transfer length, respectively. Steam generator was modeled by 4.78 MPa and 0.5 MW thermal powers. Heat exchanger bundle and steam generator were connected by pipes with 50 mm of diameter and 40 m of total length, respectively.

Operation sequence of PRHRS is follows. Water level in steam generator is decreased by postulated steam line break accident. At the water level of steam generator was reached at 3.6 m by evaporation, steam line isolation valve was closed immediately, and PRHRS actuation valves were opened. Therefore, steam will be flowed into heat exchanger bundle. Due to the heat transfer from inside of heat exchanger bundle to cooling tank, steam generator pressure will be decreased.

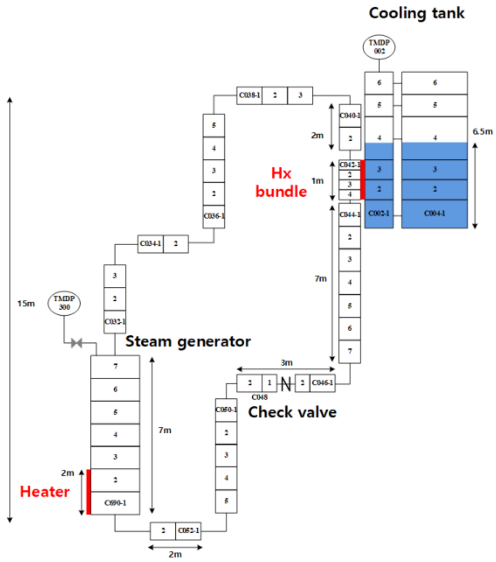


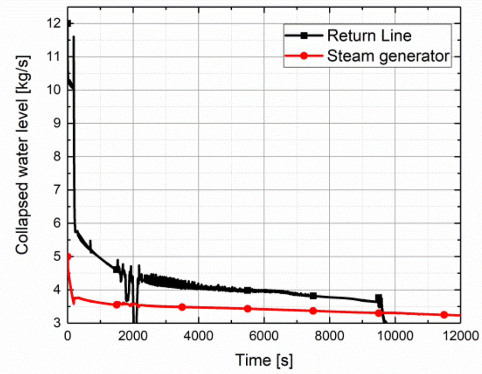
Fig. 1. Conceptual design and input node diagram of PRHRS.

3.2 Thermal Hydraulic Analysis

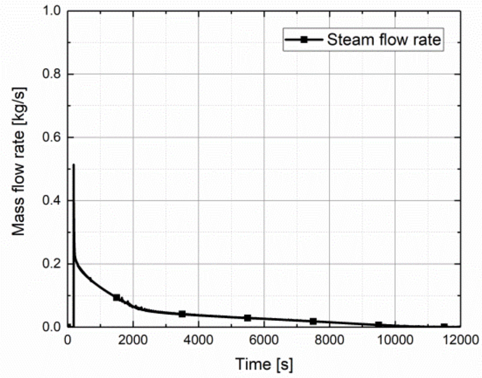
Based on the conceptual design of PRHRS, thermal hydraulic analysis was performed by MARS-KS simulation. Simulation results are shown in Fig. 2.

Steam line break was postulated by connected time dependent volume and junction component (break area: 0.01 mm^2) on the top of steam generator at 0.0 sec.

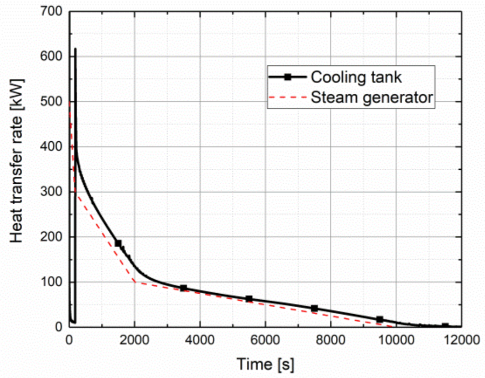
After the break, collapsed water level of steam generator was gradually decreased to 3.6 m, as shown in Fig. 2(a). At the 185 sec, steam line isolation valve on the top of steam generator was closed, and PRHRS was operated by opening of PRHRS actuation valves. Therefore, liquid level in return line was immediately dropped due to the rapid injection into steam generator, as shown in Fig. 2(b).



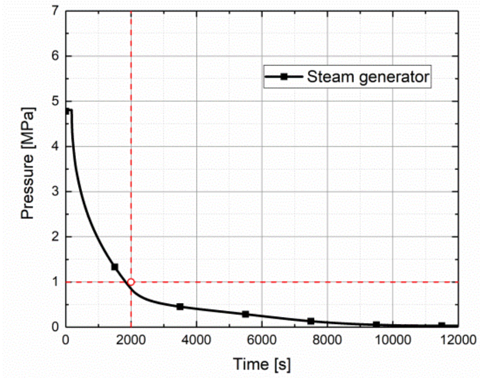
(a) Collapsed water level in steam generator and return line



(b) Steam mass flow rate in heat exchanger bundle



(c) Heat transfer rate of steam generator and cooling tank



(d) Pressure of steam generator

Fig. 2. MARS-KS simulation results of PRHRS.

In the meantime, heat transfer rate of heat exchanger bundle (cooling tank) was also rapidly increased due to the initiation of steam flow into heat exchanger bundle, as shown in Fig. 2(c). Consequently, pressure of steam generator was decreased to 1.0 MPa at 1826 sec, as shown in Fig. 2(d).

4. Application of Reliability Evaluation for PRHRS

In this section, preliminary evaluation of reliability for conceptual design of PRHRS was performed. The used values for design/operation parameters, probability density functions, and failure criteria were decided by engineering judgement.

To evaluate the reliability of PRHRS, REPAS methodology was modified as a reliability evaluation procedure for this study which was shown in Fig. 3.

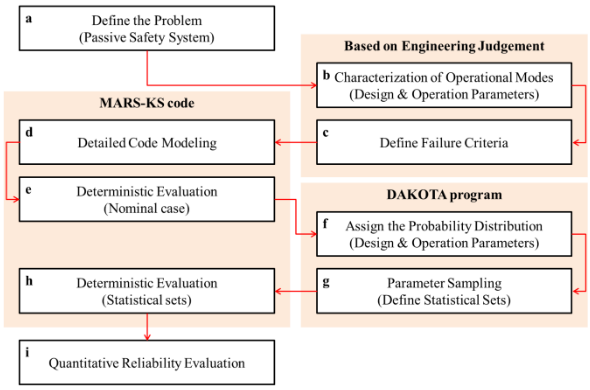


Fig. 3. Reliability evaluation procedure for PRHRS

4.1 Failure Criteria

To evaluate the reliability of PSS, failure or success criteria should be defined. In this study, Failure Criteria (FC) was defined as follows:

- FC_1: Depressurization time

$$FC_1 = \tau \text{ (at } P_{SG} = 1.0\ MPa)$$

- FC_2: ratio of total removed heat by cooling tank to total generated heat by steam generator

$$FC_2 = \frac{\int_{t=0\ s}^{t=2000\ s} \dot{Q}_{cooling\ tank}\, dt}{\int_{t=0\ s}^{t=2000\ s} \dot{Q}_{steam\ generator}\, dt} < 1.05$$

$\dot{Q}_{cooling\ tank}$: Heat transfer rate of heat exchanger bundle in cooling tank

$\dot{Q}_{steam\ generator}$: Heat transfer rate of steam generator

In this study, failure of PRHRS was defined that at least one of the failure criteria is satisfied.

4.2 Parameters Identification and Sampling

In this study, design and operation parameters which influenced to PRHRS performance were selected by engineering judgement to preliminary application of reliability evaluation for PRHRS. The selected design/operation parameters and probability density function were summarized in Table I.

Based on the selected design and operation parameters, statistical sampling of parameters was conducted using DAKOTA program. DAKOTA program provides Monte Carlo (MC) algorithm for random sampling process that includes Latin Hypercube Sampling (LHS). By Using LHS in DAKOTA program, 100 sets of parameters were selected and analyzed for reliability evaluation of PRHRS.

Table I: Design and operation parameters

Parameters	Nominal value	Probability distribution		
Initial temperature for cooling tank	298.15 K	Normal (μ: 298.15, σ: 5)		
Uncertainty of heat transfer model	0 %	Normal (μ: 0.0, σ: 0.5)		
Initial pressure of steam generator	4.78 MPa	Discrete		
		4.78 MPa	5.78 MPa	6.78 MPa
		0.85	0.1	0.05
Heat transfer coefficient for Heat loss	2 W/m^{2}K	Discrete		
		2.0	10.0	20.0
		0.7	0.2	0.1
Flow area	0.002027 m^2	Discrete		
		80 %	90 %	100 %
		0.03	0.07	0.9

4.3 Reliability Evaluation

Based on MARS-KS simulation for 100 statistical sets including nominal case, time trends of steam generator pressure, heat transfer rate of heat exchanger bundle were summarized in Fig. 4 and 5. In comparison with nominal case, analysis results of statistical sets showed large variation for steam generator pressure and heat transfer rate of heat exchanger bundle.

Through the analysis results of statistical sets, reliability of PECCS was evaluated based on failure criteria. Individual reliabilities of PECCS for FC_1 and FC_2 were 0.8686 and 0.8034, respectively. The reliability evaluation results for FC_1 and FC_2 were shown in Fig. 6 and 7, respectively. Consequently, system reliability for successful PECCS injection was evaluated by 0.7743.

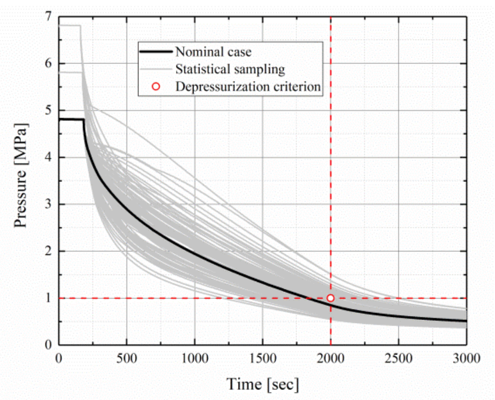


Fig. 4. Analysis results of steam generator pressure.

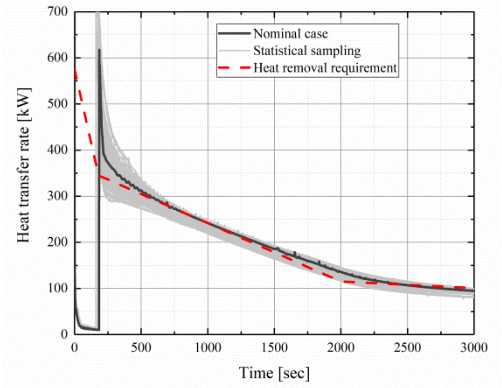


Fig. 5. Analysis results of heat transfer rate in heat exchanger bundle.

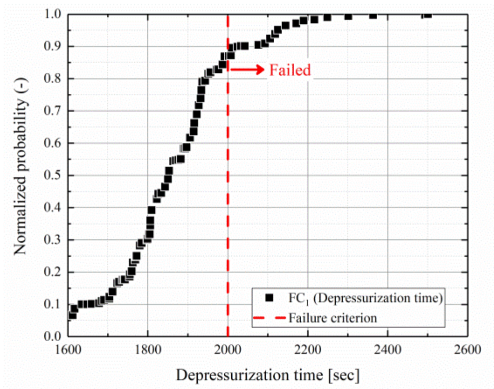


Fig. 6. Evaluation results of FC_1 (Depressurization time)

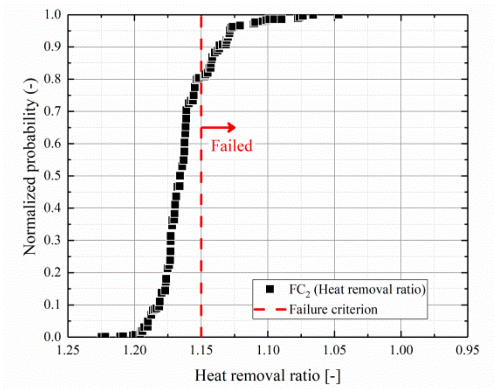


Fig. 7. Evaluation results of FC_2 (ratio of total removed heat by cooling tank to total generated heat by steam generator)

5. Conclusions

In this study, reliability evaluation methodology was preliminarily applied to PRHRS. Based on the engineering judgement, design/operation parameters and failure criteria were decided to quantitatively evaluate the reliability of PECCS. Using the DAKOTA program and MARS-KS code, 100 of statistical sets were selected and simulate to analyze the thermal hydraulic behavior. Through the analysis results, system reliability was evaluated for PRHRS with selected design/operation parameters.

The results of this study can be useful for application of reliability evaluation for passive safety system in advanced nuclear power plants. Further studies are also required to apply the actual systems on the basis of physical meaning for parameters and failure criteria.

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