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A Preliminary Study on Reliability Evaluation Methodology for Passive Safety Systems

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1. Introduction

Passive Safety Systems (PSS) are commonly utilized in Advanced Light Water Reactors (ALWR) due to their higher reliability and safety compared to active safety systems [1]. However, evaluating the performance and reliability of PSS is not straightforward as natural circulation provides less driving force compared to forced convection. As a result, the classical reliability evaluation approach alone is insufficient for assessing the reliability of PSS. A functional failure approach is also necessary [2]. This approach defines functional failure of PSS as a situation where the current performance (capacity) of PSS is insufficient to meet the required performance (load) under changed operational or design conditions, due to uncertainties in parameters and environmental conditions, even when PSS is being operated.

Several frameworks have been developed for evaluating the reliability of PSS. One such framework, RMPS (Reliability Method for Passive Safety Functions), was developed by the EU as an improvement upon the REPAS (Reliability Evaluation of Passive Safety Systems) framework. RMPS uses uncertainty propagation of physical/design parameters to evaluate PSS reliability [3]. In previous studies [4,5], the reliability evaluation methodology represented by REPAS was applied to PSS, such as the Passive Emergency Core Cooling System (PECCS) and Passive Heat Removal System (PHRS). These studies utilized a functional failure approach based on failure criteria to evaluate PSS reliability.

In this study, the reliability of PSS was evaluated using various definitions of failure criteria. The results revealed that the reliability of the system could vary depending on the criteria used to define failure.

2. Failure Criteria

In previous studies [4,5], two failure criteria were defined for evaluating the reliability of PSS. For the PECCS, preventing core damage by injecting sufficient coolant to avoid core exposure was a critical function. Therefore, the failure criteria for the PECCS were defined as core uncovered time and the ratio of the total injected coolant to break flow. Based on the defined failure criteria, the reliability of the PECCS was evaluated to be 0.8106 and 0.9332, respectively.

For the PHRS, effective heat removal was crucial for depressurizing the steam generator and cooling the reactor coolant system. Consequently, the failure criteria for the PHRS were defined as depressurization time and the ratio of the total heat removed by the cooling tank to the total heat generated by the steam generator. Based on the defined failure criteria, the reliability of the PHRS was evaluated to be 0.8686 and 0.8034, respectively.

In this study, additional failure criteria were defined for PECCS and PHRS, as follows:

- FC_{PECCS}: Pressurizer empty period

$$FC_{PECCS} = \sum_{t=0\,s}^{t=20000\,s} \tau \geq 375\ s \quad \begin{cases} \tau = 1, & \text{if } L_{PZR} < 10\ \% \\ \tau = 0, & \text{if } L_{PZR} > 10\ \% \end{cases}$$

L_{PZR}: Collapsed water level in pressurizer (PZR)

- FC_{PHRS}: ratio of accumulated mass flow rate by natural circulation

$$FC_2 = \frac{\int_{t=0\,s}^{t=3000\,s} \dot{m}_{PHRS}\, dt}{\int_{t=0\,s}^{t=3000\,s} \dot{m}_{PHRS,ref}\, dt} < 0.99$$

$\dot{m}_{PHRS}$: Mass flow rate by natural circulation of PHRS

$\dot{m}_{PHRS,ref}$: Mass flow rate by natural circulation of PHRS in nominal case

Based on the defined failure criteria, reliability evaluation was performed by previous study's [4,5] methodology and parameter condition.

3. Reliability Evaluation Results

The deterministic evaluation result of PECCS is shown in Fig. 1. The collapsed water level in the PZR varied with changes in design and operational parameters. For several cases of statistical sampling in PECCS analysis, the collapsed water level in the PZR did not recover due to functional failure of PECCS. The reliability of PECCS was evaluated based on the pressurizer empty period, which resulted in a value of 0.8467, as shown in Fig. 2.

For PHRS, deterministic thermal-hydraulic analysis results, including nominal and statistical sampling cases, are shown in Fig. 3. In the early period of PHRS operation, steam mass flow rate caused by natural circulation in PHRS showed a large variation. However, after 500 seconds, the steam flow rate almost converged to the nominal case. Therefore, more than 93.8% of statistical sampling cases met the success condition. Finally, the reliability of PHRS, with the ratio of the accumulated mass flow rate by natural circulation, was evaluated to be 0.9379, as shown in Fig. 4.

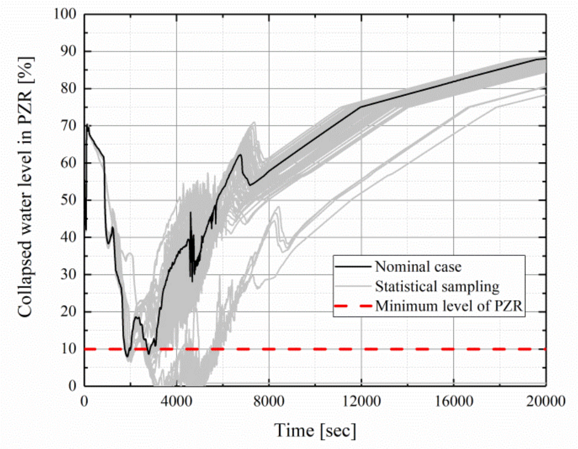

Fig. 1. Deterministic thermal-hydraulic analysis results of PECCS showing collapsed water level in PZR.

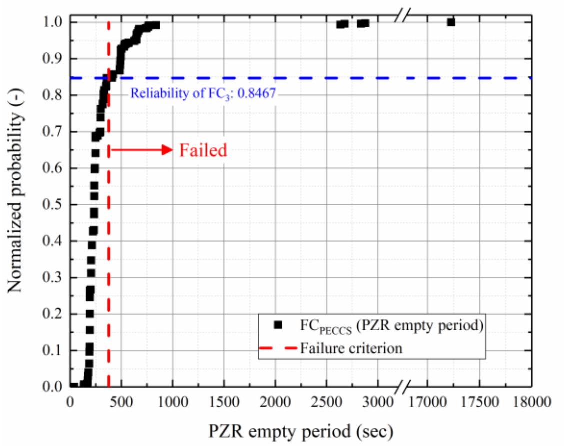

Fig. 2. Reliability evaluation results of FC_{PECCS}.

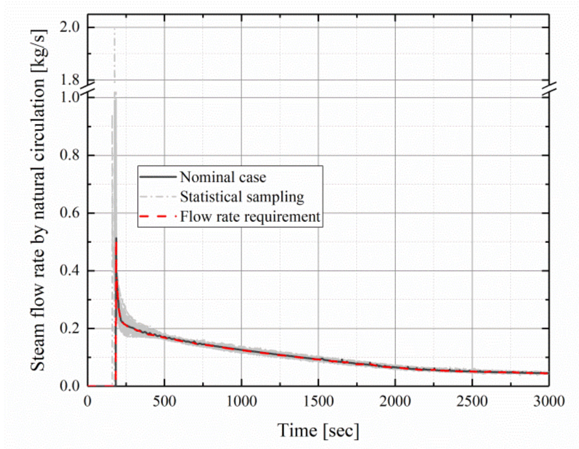

Fig. 3. Deterministic thermal-hydraulic analysis results of PHRS showing steam mass flow rate caused by natural circulation.

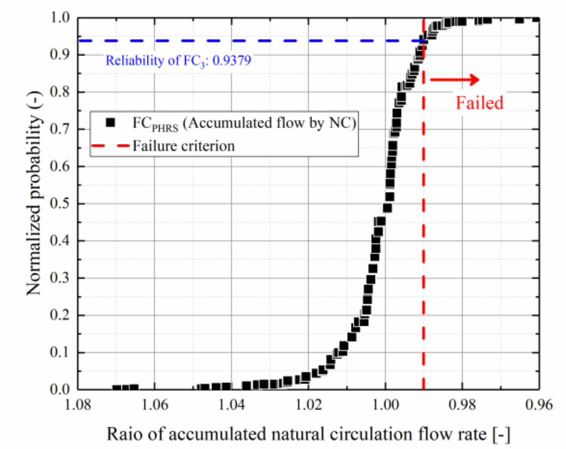

Fig. 4. Reliability evaluation results of FC_{PHRS}.

3. Conclusions

In this study, reliability evaluation methodology was applied to PECCS and PHRS with different definition of failure criteria. Failure criteria were crucial terminology to reliability evaluation of PSS. Consequently, reliability of PECCS and PHRS were changed than previous studies.

In terms of safety of nuclear reactor using PSS, for the various points of view, it is important to consider various phenomena and parameters. Therefore, failure criteria should be defined to represent the nuclear reactor safety for the specific phenomena or accidents.

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