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Study on Performance Evaluation Methodology for Passive Safety System

Jeehee Lee [a*], Seong-Su Jeon [a], Su Hyun Hwang [a], Ju-Yeop Park [b]
[a] *FNC Tech., Heungdeok IT Valley, Heungdeok 1-ro, Giheung-gu, Yongin-si, Gyeonggi-do, 446-908, Korea*
[b] *Korea Institute of Nuclear Safety, 62 Kwahak-ro, Yuseong, Daejeon, Korea*
[*] *Corresponding author: capable91@fnctech.com*

1. Introduction

As the introduction of Passive Safety Systems (PSSs) increases in Advanced Light Water Reactor (ALWR), there are limitations to the existing performance evaluation methodologies for conventional safety systems. Conventional safety systems operate using an external power source, so as long as there is a stable power supply, there are no problems with their operation. However, PSSs rely solely on natural phenomena, such as gravity and density differences, to operate, making their driving force relatively weaker. As a result, PSSs may not perform adequately due to pressure and heat losses in the system, even in the absence of mechanical or electrical failure. Therefore, an improved performance evaluation methodology is required that takes the characteristics of PSSs into account when evaluating the ALWR with PSSs. In this study, a universally applicable performance evaluation methodology is being developed to propose safety analysis modeling guidelines and performance improvement considerations for nuclear power plants with PSSs.

2. Existing Passive Safety System Concept Review

The most representative ALWRs that have adopted PSSs include AP1000 [1], ESBWR [2], iPower [3], and SMART100 [4]. These systems can be classified into three types based on their operating principles and functions.

- Passive Heat Removal System (PHRS)
- Passive Emergency Core Cooling System (PECCS)
- Passive Containment Cooling System (PCCS)

2.1 Passive Heat Removal System (PHRS)

PHRS is a safety system that removes heat generated in the reactor core or steam generators by cooling the heated fluid using a heat exchanger located in an upper pool. The Passive Heat Removal System (PRHRS) of AP1000, the Isolation Condenser System (ICS) of ESBWR, the Passive Auxiliary Feedwater System (PAFS) of iPower, and the PRHRS of SMART100 are all PHRS-type PSSs. These systems utilize natural circulation generated by the density difference of single-phase or two-phase fluids, replacing the existing residual heat removal system and auxiliary feedwater system to perform safety functions.

2.2 Passive Emergency Core Cooling System (PECCS)

Passive Emergency Core Cooling Systems (PECCS) are designed to inject safety injection water directly into the core to replenish the coolant inventory and mitigate accidents. The representative PECCS systems include AP1000's Passive Core Cooling System (PXS), iPower's PECCS, and SMART100's Passive Safety Injection System (PSIS). These systems replace the existing Emergency Core Cooling System (ECCS) that relies on pumps with natural circulation flow utilizing gravity and head differences. They all have an independent tank that replaces the high-pressure/low-pressure safety injection system.

2.3 Passive Containment Cooling System (PCCS)

Passive Containment Cooling Systems (PCCSs) are designed to remove the energy released from the RCS due to an accident by utilizing a final heat sink outside the containment. In contrast to conventional safety systems that rely on water spray inside the containment to remove energy, PCCSs use natural circulation, condensation on the containment wall, and heat exchangers to remove energy. The AP1000 PCCS uses condensation on the containment wall, while the PCCSs of the ESBWR, iPower, and SMART100 use heat exchangers to remove energy from RCS.

3. Development of Performance Evaluation Methodology for PSS

A performance evaluation methodology being developed for PSSs is presented in Fig. 1 [5]. The methodology comprises a total of seven stages, and each stage is described as follows:

1) Review of Target PSS Design

In step 1, the performance evaluation process of a particular PSS involves selecting the system and reviewing relevant design information such as the system's geometry and location, design requirements, actuation signal, and initial conditions.

2) Identification of the Major Thermal-Hydraulic (TH) Phenomena of PSS

During step 2 of the performance evaluation methodology for PSSs, the Phenomena Identification and Ranking Table (PIRT) of the target PSS is examined, and significant thermal-hydraulic (TH) phenomena at the local, component and system levels are identified through further review of TH phenomena related to the system. These significant TH phenomena are then used to determine the design requirements that need to be assessed during the performance evaluation and to select appropriate system analysis codes for the evaluation.

3) Assessment of Prediction Capability of System Analysis Code for PSS TH Phenomena

In step 3, the system thermal-hydraulic analysis code is chosen based on the major TH phenomena identified in step 2. The capability of chosen code to accurately predict thermal-hydraulic phenomena is confirmed through validation using separate effect tests (SETs) and integral effect tests (IETs). The model and correlation uncertainties of code are also determined in this process.

4) Development of Reference Analysis Model for Target PSS

Before conducting performance evaluation, step 4 involves creating a reference input model for the target PSS, while considering the effect assessment of major performance issues and parameter combinations to be analyzed in steps 5 and 6.

5) Identification of Major Performance Issues for Target PSS

In this performance evaluation methodology for PSSs in nuclear power plants, step 5 is important in identifying the major performance issues for the target PSS. Due to the complexity of various systems and types of PSSs in the plant, it is challenging to identify the specific issues that affect individual PSSs. Therefore, step 5 involves generating a list of various performance issues (5-1) and a probabilistic set (5-2) of parameter combinations, which are then evaluated. The list of performance issues is derived by reviewing existing studies and literature and considering the perspectives of regulatory bodies and experts. Meanwhile, the probabilistic set is generated by defining failure criteria and assigning probability distributions to parameters based on steps in the reliability evaluation methodology. Finally, the reference input model developed in step 4 is utilized to perform the evaluation of steps 5-1 and 5-2, leading to the identification of major performance issues for the target PSS.

6) Nuclear Steam Supply System (NSSS) coupled PSS Performance Evaluation

Step 6 of the performance evaluation methodology involves coupling the PSS analysis model with the NSSS model to evaluate the PSS performance. The selection of the evaluation model should take into account the transient and accident scenarios in which the target PSS operates. During the coupled evaluation, the major performance issues identified in step 5, including essential performance issues and major parameter combinations, should be evaluated, and additional issues related to NSSS operation should also be considered. Moreover, the combined effect of these factors should be assessed.

7) Derivation of Considerations for Design Improvement and Safety Analysis Guidelines for PSS

Step 7 of this performance evaluation methodology involves using the results obtained from steps 5 and 6 to derive design improvement considerations aimed at enhancing the safety and performance of the target PSS. Additionally, modeling and safety analysis guidelines for the PSS are also derived based on the evaluation results.

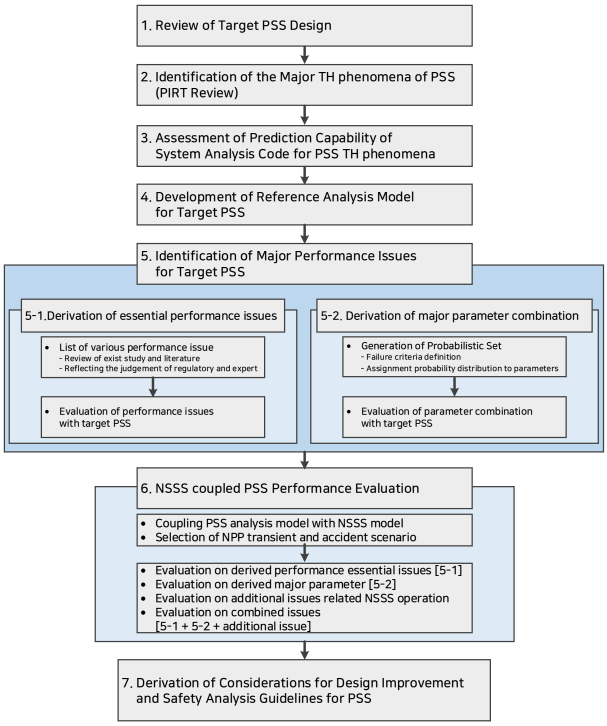

Fig. 1. Performance Evaluation Methodology for Passive Safety System [5]

4. Conclusions

This study is developing a performance evaluation methodology for PSSs in nuclear power plants, taking into account the characteristics of these systems. To achieve this goal, a survey was conducted to examine the current status of PSSs and analyze their features. Additionally, a seven-step performance evaluation methodology was proposed, and the applicability of newly implemented steps for PSSs is being analyzed [5]. In the future, the proposed methodology will be evaluated using actual nuclear power plants with PSSs, and considerations for safety analysis modeling guidelines and performance improvement will be derived through performance evaluations.

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