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Preliminary Application of Reliability Evaluation Methodology for Passive Safety System

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1. Introduction

The numerous 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 adopted to Advanced Light Water Reactor (ALWR) through that was considered to have higher reliability and safety than active safety system due to its low dependency on the operator and external power supply.

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, several reliability evaluation methodologies were compared and major issues for PSS were also suggested.

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 changed 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, preliminary assessment was conducted by application of reliability evaluation methodology to conceptual design of Passive Emergency Core Cooling System (PECCS). 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 PECCS 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 PECCS performance.

3. Passive Safety System

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

3.1 Conceptual Design of Passive Emergency Core Cooling System

Passive Emergency Core Cooling System (PECCS) was selected as a Passive Safety System (PSS) to apply reliability evaluation methodology.

Conceptual design of PECCS for small modular reactor was depicted in Fig. 1. PECCS consisted of Core Makeup Tank (CMT), Safety Injection Tank (SIT), and Reactor Pressure Vessel (RPV). CMT and SIT were modeled by 35 m^3 and 90 m^3 of liquid volume with 6 m and 9 m of liquid height, respectively. RPV was modeled by 15 MPa and 1 MW thermal power including pressurizer and core. CMT/SIT and RPV were connected by pipes with 54 mm of diameter and 100/125 m of total length, respectively.

SIT was filled with 40 ℃ and 0.1 MPa of water and initially isolated from RPV by SIT check valve and SIT actuation valve. Inlet of the CMT was directly connected to RPV outlet and filled with 40 ℃ and 15 MPa of water.

PECCS would be operated by following sequence. CMT actuation valve will be opened by low pressure signal of pressurizer (< 10 MPa) due to the Small Break Loss Of Coolant Accident (SBLOCA). Through the CMT actuation, emergency coolant in CMT was injected into RPV. In spite of CMT injection, RPV could be depressurized by continuous break flow. If low-low pressure signal of pressurizer (< 1.5 MPa) was assigned, emergency coolant in SIT would be injected into RPV by opened of SIT actuation valve.

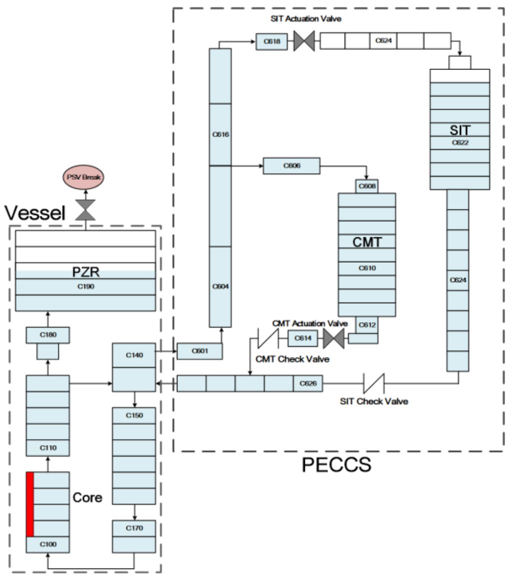


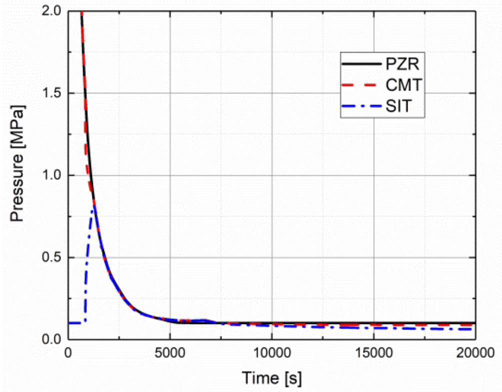
Fig. 1. Conceptual design and input node diagram of PECCS.

3.2 Thermal Hydraulic Analysis

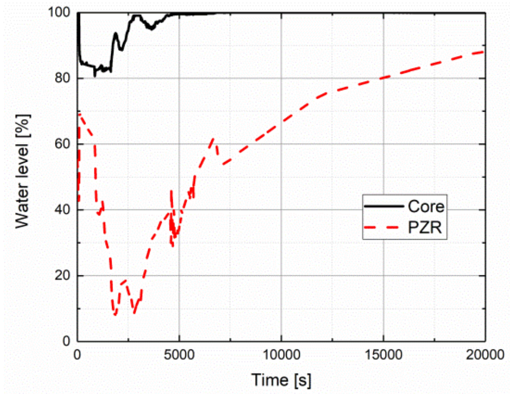
Based on the conceptual design of PECCS, thermal hydraulic analysis was performed by MARS-KS simulation. Simulation results are shown in Fig. 2 and 3.

SBLOCA was postulated by opening of safety valve (break area: 0.001 mm^2) on the top of pressurizer due to malfunction at 10 sec.

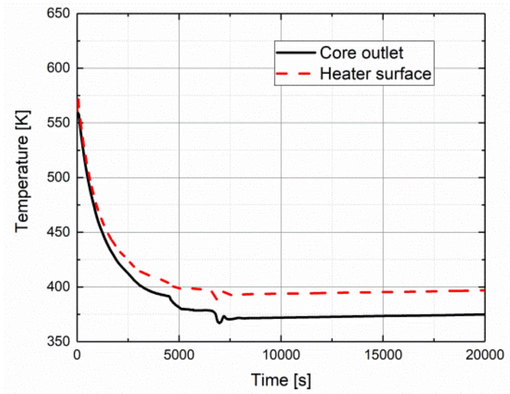
After the break, RPV was rapidly depressurized by 10 MPa at 42 sec (CMT actuation time by low pressure signal) and 1.5 MPa at 837 sec (SIT actuation time by low-low pressure signal), as shown in Fig. 2(a). Finally, RPV pressure was maintained by 0.25 MPa.



(a) Pressure of RPV, CMT and SIT



(b) Collapsed water level in RPV

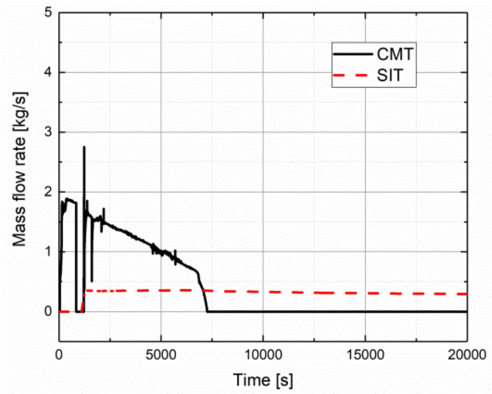


(c) Temperature of core outlet and heater surface

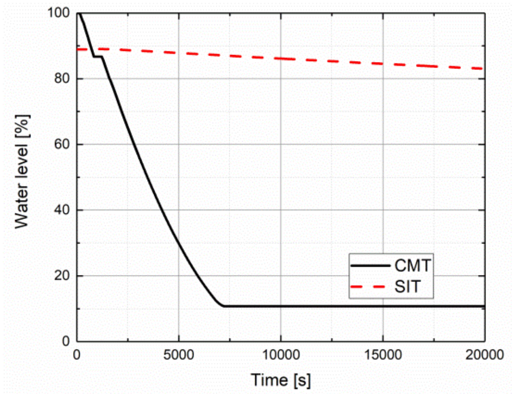
Fig. 2. MARS-KS simulation results of PECCS.

During the accident, collapsed water level of core and pressurizer in RPV were rapidly changed by flashing, break flow and safety injection, as shown in Fig. 2(b). In the core, collapsed liquid level was immediately dropped by 80 % by flashing due to the depressurization of RPV. At this time, collapsed water level of pressurizer was rapidly increased due to the increasing of void in core. After the initial flashing in core, both water levels were slowly reduced by compensation of continuous break flow and CMT injection. At 837 sec, collapsed water level of pressurizer was immediately dropped by discharge from RPV to SIT inlet due to SIT actuation valve open. However, pressurizer water level was recovered after 5000 sec by SIT and CMT injection.

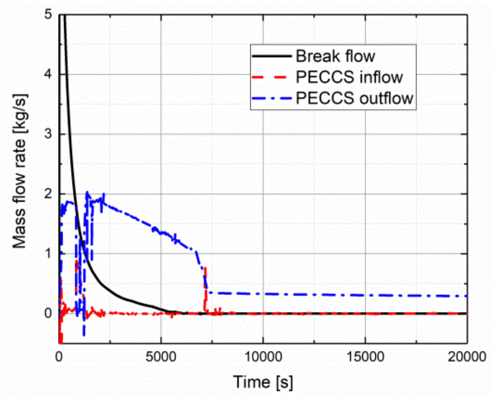
Core outlet temperature was decreased when saturation temperature of liquid was reached core outlet temperature by depressurization. Heater surface temperature was also decreased by heat removal due to intensive nucleate boiling and flashing of liquid, as shown in Fig. 2(c).



(a) Mass flow rate of CMT and SIT injection



(b) Collapsed water level in CMT and SIT



(c) Mass flow rate of break and PECCS injection

Fig. 3. MARS-KS simulation results of PECCS injection flow.

At the early period of SBLOCA (~837 sec), break flow rate was higher than emergency coolant injection flow rate by CMT, because of large pressure difference between RPV and environment. At this period, nearly constant flow rate was injected by CMT, as shown in Fig. 3(a). However, CMT flow rate was rapidly stopped due to discharge from RPV to SIT when SIT actuation valve was opened. After the pressure balance between RPV and SIT, CMT injection flow rate was recovered and SIT injection was started.

CMT injection flow rate was continuously decreased by reducing of CMT water level, as shown in Fig. 3(b). In this reference analysis results, CMT emptied out in 7240 sec. Meanwhile, constant flow rate was injected by SIT and its water level was maintained above 80 %.

Consequently, total flow rate of PECCS was larger than break flow after SIT actuation, as shown in Fig. 3(c). Furthermore, in terms of long-term cooling, total amount of injected coolant by PECCS was sufficient to compensate the break flow, as shown in Fig. 4.

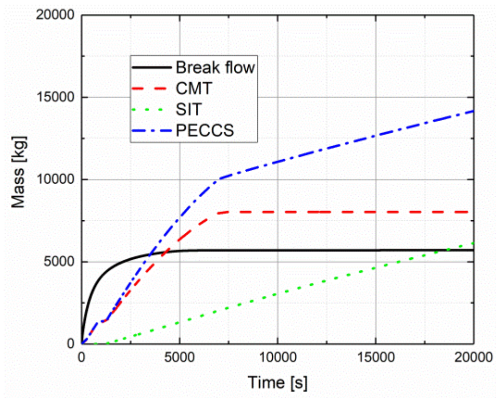


Fig. 4. Total amount of injected coolant and break flow.

4. Application of Reliability Evaluation for PSS

In this section, preliminary evaluation of reliability for conceptual design of PECCS 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 PECCS, REPAS methodology was modified as a reliability evaluation procedure for this study which was shown in Fig. 5.

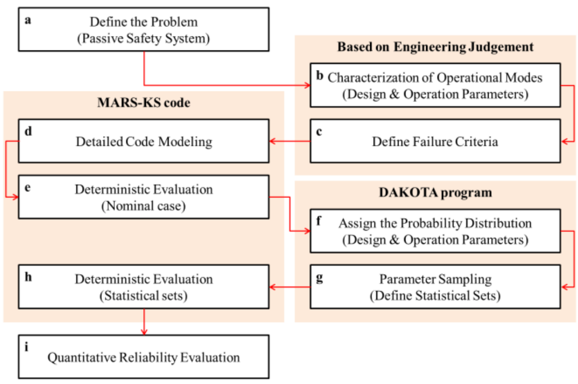


Fig. 5. Reliability evaluation procedure for PECCS

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: Core uncovered time

$$FC_1 = \sum_{t=0\,s}^{t=5000\,s} \tau \geq 1500\,s \quad \begin{cases} \tau = 1, & \text{if } L_{core} < 85\,\% \\ \tau = 0, & \text{if } L_{core} > 85\,\% \end{cases}$$

L_{core}: Collapsed water level in core

- FC_2: The ratio of total amount of injected coolant to break flow

$$FC_2 = \frac{\int_{t=0\,s}^{t=5000\,s} \dot{m}_{PECCS}\,dt}{\int_{t=0\,s}^{t=5000\,s} \dot{m}_{break}\,dt} < 1.3$$

$\dot{m}_{PECCS}$: Mass flow rate by PECCS injection
$\dot{m}_{break}$: Mass flow rate by break

- FC_3: Maximum heater surface temperature

$$FC_3 = T_{hs,max} > 1477\,K$$

$T_{hs,max}$: Maximum temperature of heater surface

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

Table I: Design and operation parameters

<table>
<tr><th>Parameters</th><th>Nominal value</th><th colspan="6">Probability distribution</th></tr>
<tr><td>Ambient temperature for heat loss</td><td>298.15 K</td><td colspan="6">Normal
(μ: 298.15, σ: 5)</td></tr>
<tr><td rowspan="3">Valve opening area</td><td rowspan="3">0.002041 m²</td><td colspan="6">Discrete</td></tr>
<tr><td colspan="2">10 %</td><td colspan="2">50 %</td><td colspan="2">100 %</td></tr>
<tr><td colspan="2">0.05</td><td colspan="2">0.1</td><td colspan="2">0.85</td></tr>
<tr><td rowspan="3">Core power</td><td rowspan="3">1 MW</td><td colspan="6">Discrete</td></tr>
<tr><td colspan="2">20 %</td><td colspan="2">50 %</td><td colspan="2">100 %</td></tr>
<tr><td colspan="2">0.1</td><td colspan="2">0.2</td><td colspan="2">0.7</td></tr>
<tr><td rowspan="3">Heat transfer coefficient for Heat loss</td><td rowspan="3">2 W/m²K</td><td colspan="6">Discrete</td></tr>
<tr><td colspan="2">2.0</td><td colspan="2">8.0</td><td colspan="2">15.0</td></tr>
<tr><td colspan="2">0.7</td><td colspan="2">0.2</td><td colspan="2">0.1</td></tr>
<tr><td rowspan="3">Flow area</td><td rowspan="3">0.00229 m²</td><td colspan="6">Discrete</td></tr>
<tr><td colspan="3">90 %</td><td colspan="3">100 %</td></tr>
<tr><td colspan="3">0.1</td><td colspan="3">0.9</td></tr>
</table>

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, 88 sets of parameters were selected and analyzed for reliability evaluation of PECCS.

4.3 Reliability Evaluation

Based on MARS-KS simulation for 82 statistical sets including nominal case, time trends of collapsed water level in core, PECCS injection flow rate, and maximum heater surface temperature were summarized in Fig. 6 ~ 8.

In comparison with nominal case, analysis results of statistical sets showed large variation for collapsed water level in core region and PECCS injection flow rate, as shown in Fig. 6 and 7, respectively. However, maximum heater surface temperature was only varied from +15.5 K to −33.1 K, as shown in Fig. 8.

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 0.8106 and 0.9332, respectively. The reliability evaluation results for FC_1 and FC_2 were shown in Fig. 9 and 10, respectively. For the FC_3 (maximum heater surface temperature), analysis results for all statistical sets were satisfied failure criteria 3. Therefore, reliability for FC_3 was unity. Consequently, system reliability for successful PECCS injection was evaluated by 0.8106.

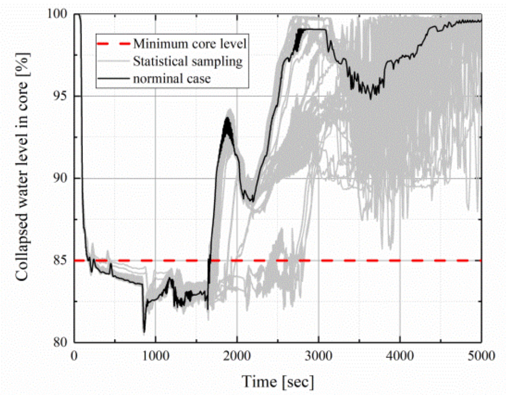


Fig. 6. Analysis results of collapsed water level in core.

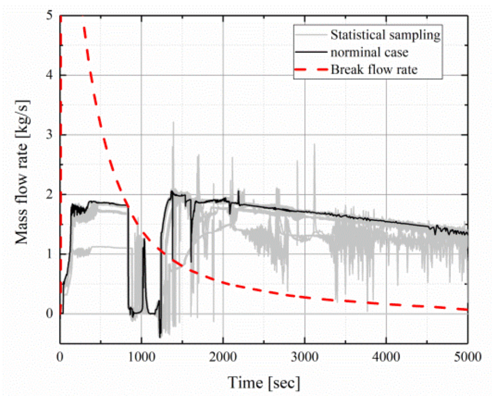


Fig. 7. Analysis results of PECCS injection flow rate.

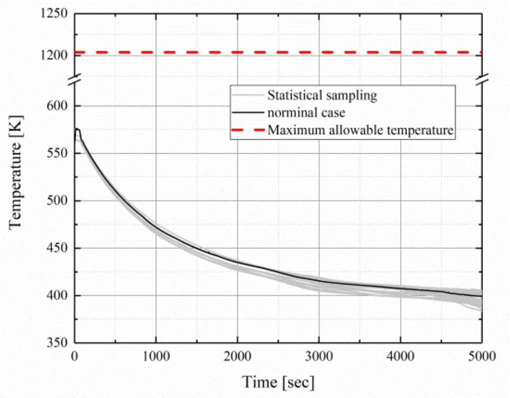


Fig. 8. Analysis results of maximum heater surface temperature.

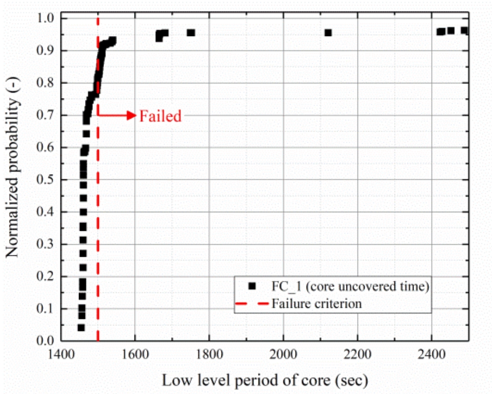


Fig. 9. Evaluation results of FC_1 (core uncovered time)

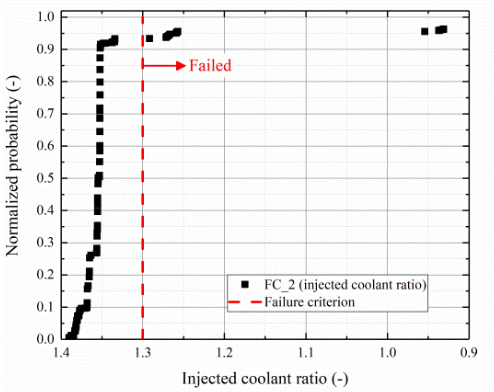


Fig. 10. Evaluation results of FC_2 (ratio of total amount of injected coolant to break flow)

5. Conclusions

In this study, reliability evaluation methodology was preliminarily applied to PECCS. 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, 82 of statistical sets were selected and simulate to analyze the thermal hydraulic behavior. Through the analysis results, system reliability was evaluated for PECCS 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.

ACKNOWLEDGEMENT

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