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Estimation of Conditional Exceedance Probability for LBLOCA using Monte-Carlo and Alternative Method

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1. Introduction

Studies on the integrated approach of deterministic and probabilistic methods have been carried out. The key part of the integrated approach is to determine a functional failure probability or a conditional exceedance probability (CEP). However, in most cases, it is difficult to obtain the CEP because a functional failure occurs in rare events that have low probabilities (i.e., order of 10^{-3} or less); so that it requires a lot of computational costs or additional statistical techniques. Some have used the statistical method, but the direct Monte-Carlo (MC) method has been widely used to calculate the CEP as the computational capability improves.

Although a utilization of the direct MC method has been increasing, most of the previous studies using the MC method have not made statistical estimations, and it is still being debated that how many samples are required to obtain the result with low uncertainty and high convergence. Therefore, in this study, assuming the 10% power uprate of APR-1400, the uncertainty quantification analysis of LBLOCA was conducted by using the direct MC method. Based on the PCT data obtained from different sample sizes and different sampling methods, the CEPs (i.e., probability that PCT would exceed the LOCA safety limit of 1477 K), and their 95% confidence intervals (CIs) were estimated. Then, the results of MC method were compared with those of Johnson's normal distribution transformation method. Based on these analyses, the MC sample size and sampling method needed to yield reasonable CEP for LBLOCA, were evaluated.

2. Model description and MC calculations

Assuming the 10% power uprate of APR-1400, the LBLOCA by 100 % double-ended guillotine break at the reactor coolant pump discharge leg was considered to be analyzed, and the transient was analyzed by using MARS-KS code. In the scenario, two SIPs and two SITs were assumed to be available reflecting previous probabilistic risk assessment results [1]. The 18 uncertainty parameters were considered for uncertainty propagation and quantification [2].

Based on the direct MC method, 100, 200, 500, 1000, 2000 samples were made by simple random sampling (SRS) and latin hypercube sampling (LHS), and corresponding calculations were performed. In addition, the calculations using 5000 samples with SRS were performed as the reference of MC calculations. Fig. 1 shows the probability density and cumulative probability of PCT for the reference calculation. The most of PCTs appeared in the reflood phase, and some cases beyond PCT limit of 1477 K were found.

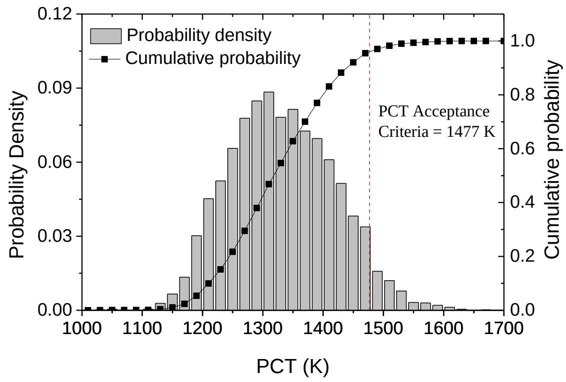

Fig. 1. Probability density and cumulative probability of PCT for reference calculation.

3. Results and Discussions

3.1 Direct Monte-Carlo method

From the PCT data, the CEPs and their 95% CIs with respect to sample size and sampling method were estimated. The 95% CI for CEP ($\mathrm{CI}_{P_{exc},0.95}$) from samples can be expressed as following;

$$\mathrm{CI}_{P_{exc},0.95} = P_{exc} \pm 1.96 \cdot SE_{P_{exc}} = P_{exc} \pm 1.96\sqrt{\frac{P_{exc}\cdot(1-P_{exc})}{n}} \quad (1)$$

where P_{exc} is the CEP from samples, $SE_{P_{exc}}$ is the standard error of CEP. Table 1 shows the CEPs and their standard error with respect to sample size and sampling method. Then, $\mathrm{CI}_{P_{exc},0.95}$ was calculated by using Equation (1) and Table 1.

Table 1. Summary of MC results for CEP

Sample size	SRS		LHS	
	P_{exc}	$SE_{P_{exc}}$	P_{exc}	$SE_{P_{exc}}$
100	0.0600	0.0237	0.0700	0.0255
200	0.0700	0.0180	0.0750	0.0186
500	0.0520	0.0099	0.0780	0.0120
1000	0.0720	0.0082	0.0680	0.0080
2000	0.0715	0.0058	0.0690	0.0057
5000	0.0662	0.0035		

3.2 Comparison with Johnson's normal distribution transformation method for CEP

As an alternative way to calculate the CEP, the transformation method, in which the PCT distribution obtained from small samples, is transformed into normal distribution, was proposed [3]. The PCT data for all MC cases were attempted to be converted into normal distribution by the Johnson transformation [4]. As a result, the normality was satisfied only for relatively small (i.e. less than 1000) sample sizes. However, in the cases of large sample sizes (i.e. 2000 for LHS and 5000 for SRS), normality was not satisfied despite the Johnson transformation.

The CEPs for the sample size of 1000 or less were calculated by the Johnson transformation method. Fig. 2 shows a comparison between the results of the MC and the Johnson transformation method. The CEP results of the Johnson transformation method using data of 500 samples or less showed a large variation for sample size and sampling method, and most of the results were not within 95% CI of the reference result. The results of the Johnson transformation method for 1000 samples were within the 95% CI of the reference and did not show much difference from the results of the MC method. However, it does not seem to have a benefit in terms of the computational cost.

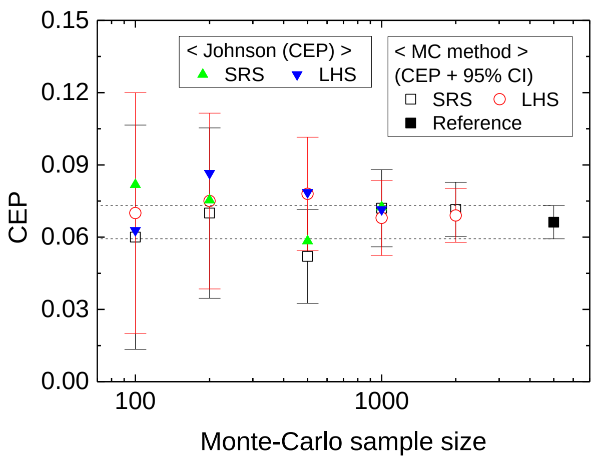

Fig. 2. Comparison of CEP by Monte-Carlo and Johnson transformation method.

Conservative 95% confidence limit have not been applied to the studies of CEP so far. However, as shown in the figure, when the sample size is small, the width of 95 % CIs of CEP using the MC method were too large. It seemed that the 95% confidence intervals became narrow to an acceptable level when the sample size was 1000 or more. And for these cases, the CEP values of MC method also were within the 95% CI of the reference result and tended to converge. In addition, when the sample size was less than 1000, the difference of CEP values between SRS and LHS methods were quite large, whereas when the sample size was 1000 or more, the effect of sampling methods on CEP results was shown to be relatively small. However, for MC calculations with 1000 or more samples, the decreasing amount of standard error with respect to increase in sample size was too small (i.e., standard error of CEP was reduced only by less than ~ 0.0023, when the sample size increases from 1000 to 2000 and from 2000 and 5000 as shown in Table 5). Therefore, in this study, considering both computational cost and benefit of increase in sample size, it was found that the MC method using 1,000 samples could yield reasonable CEP result.

4. Conclusions

In this study, assuming the 10% power uprate of APR-1400, the uncertainty quantification analysis of LBLOCA with 18 uncertainty parameters was performed by using the direct MC method. Based on the PCT data obtained from different sample sizes and different sampling methods, the CEPs and their 95% confidence intervals were estimated, and the results of MC method were compared with those of the Johnson normal distribution transformation method.

The limitations of the Johnson's normal distribution transformation method (i.e., large variation and inaccuracy) were identified, and it was confirmed that the MC method could replace them. Considering all of computational cost, benefit of increase in sample size and statistics convergence, it was found that the MC method using 1000 samples could remedy the shortcomings of Johnson's transformation method, and it could yield reasonable CEP results. In addition, when the sample size was 1000 or more, the effect of sampling methods was not significant.

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