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MCNP5 Benchmarking Calculations of HI-STAR 100 Cask Criticality Safety

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1. Introduction

As the first task in used nuclear fuel cask design analysis, we have performed validation of criticality safety calculation for the HI-STAR 100 system with sample input files in the safety analysis report (SAR). The HI-STAR 100 is a storage and transport cask system for spent nuclear fuel designed by Holtec International [1]. It has various multi-purpose cask (MPC) models depending on the number of fuel assemblies to be stored, 24, 32, and 68, and fuel types (PWR or BWR). The SAR of HI-STAR 100 uses MCNP4a code to perform criticality safety calculations and offers example MCNP4a input files used for the criticality safety calculations. This paper presents results from running the MCNP5 code [2,3] for criticality safety and compares the output with that in the SAR as the validation for the correct use of the computer code.

The SAR presents criticality safety calculations with the Monte Carlo code MCNP4a. In the SAR, there are two sample MCNP4a input files for criticality calculation for MPC-24 storing 24 WE-15X15F01 PWR fuel assemblies and for MPC-68 storing 68 GE8X8C04 BWR fuel assemblies.

2. Upper-bound uncertainty estimation

2.1 Definition of the maximum multiplication factor

The HI-STAR 100 SAR determines [1] the maximum effective multiplication factor $k_{eff}^{\max}$ accounting for statistical fluctuations and code bias:

$$k_{eff}^{\max} = k_c + \alpha_c\sigma_c + \Delta k_b + \alpha_b\sigma_b\,, \tag{1}$$

k_{eff} = effective multiplication factor with MCNP5,

$\alpha_c\sigma_c$ = upper bound value for a one-sided statistical tolerance limit with 95% probability at the 95% confidence level. It consists of the multiplier α_c and a standard deviation σ_c,

Δk_b = systematic bias in the calculations (code dependent),

$\alpha_b\sigma_b$ = standard deviation σ_b of the bias and a multiplier α_b for 95% probability at the 95% confidence level.

The MCNP5 code produces the result of criticality simulation as an average value of the multiplication factor k_{eff} and a standard deviation α_c. The systematic bias Δk_b and the standard deviation α_b of the bias in MCNP4a were calculated to 0.0021 and 0.0007 by benchmark criticality calculation of Holtec International [1].

The maximum k_{eff} can be calculated with an average of effective multiplication factors over active batches of neutron transport calculations simulated, the standard deviation calculated by the code, and the systematic errors. The maximum k_{eff} should be below 0.95 for criticality safety.

2.2 Multiplier α estimation

The multiplier α is determined through the double probability inequality [4]:

$$P[P(X \le \bar{x} + \alpha s) \ge p] \ge \gamma\,, \tag{2}$$

where $\bar{x}$ is the sample mean, s is the sample standard deviation, p is the probability corresponding to the tolerance limit, and γ is the confidence level. For the inner probability inequality of Eq. (2), it is related to the probability equation:

$$P(Z \le z_p) = p\,, \tag{3}$$

where z_p is the 100p percentile value of the standard normal distribution. To match the inner probability inequality of (2) up with (3), the inequality is derived:

$$\frac{\bar{x} + \alpha s - \mu}{\sigma} \ge z_p\,, \tag{4}$$

where μ is the population mean and σ is the population standard deviation. The inner probability inequality of Eq. (2) is modified to inequality equation (4). Therefore, we should find the minimum value of α satisfying a one-sided statistical tolerance limit with probability p at the confidence level of γ. In the end, the probability density function for non-central t-distribution is derived from (2) and (4):

$$P(T_{n-1,\delta} \le \sqrt{n}\alpha \mid \delta = \sqrt{n}z_p) = \gamma\,, \tag{5}$$

where $T_{\upsilon,\delta}$ is the non-central t-distribution variable including the degree of freedom υ and the non-central parameter δ. The value of α is calculated with a *nctcdf* function in MATLAB easily. For a tolerance limit with 95% probability at the 95% confidence level and a sample size of 100, the multiplier α is 1.9267; however, it is rounded off to a more conservative value of 2.00.

3. Results and discussion

3.1 MPC-24 criticality

The first sample input file shows criticality calculations of the MPC-24 containing 24 fresh WE 15X15F01 fuel assemblies. Fresh fuel assemblies usually have a larger k_{eff} than spent fuels; therefore, the simulation in the HI-STAR 100 contains a conservative factor by representing fresh fuel assemblies rather than spent fuel assemblies.

During normal transportation conditions the HI-STAR 100 system is dry (no moderator), and thus, the reactivity is very low (k_{eff} < 0.50). However, the HI-STAR 100 system for loading and unloading operations, as well as for hypothetical accident conditions, is assumed flooded, and thus, represents the limiting case in terms of reactivity. In addition, the calculations were performed in room temperature where the cask system would have the highest reactivity in the flooded condition.

In the sample input files for criticality analysis, the multiplication factor is obtained through 10,000 neutron histories per batch, and a total of 120 batches, including 100 active batches. The input file also contains a $S(\alpha,\beta)$ thermal neutron treatment to present light water moderating effect.

The WE 15X15F01 fuel assembly has 208 U-235 fuel rods with 4.1 wt% of enrichment and active fuel length of 150 inches. Table I shows results from the SAR and our MCNP5 benchmarking calculations.

Table I: Criticality calculation for the MPC-24 cask

	SAR result	MCNP5
k_{eff}	0.93500	0.93381
σ_c	0.00090	0.00089
$\alpha_c\sigma_c$	0.00180	0.00178
$\Delta k_b + \alpha_b\sigma_b$	0.00280	0.00280
$k_{eff}^{\max}$	0.93960	0.93839
$k_{eff}^{\max}$ difference (pcm)	121	

We calculated the maximum k_{eff} for MCNP5 using the systematic errors equal to those for MCNP4a. For the MPC-24 cask, the calculated maximum k_{eff} value has a difference of 121 pcm from the SAR result, which is within 2σ; therefore, it is considered that the calculation of criticality safety is valid with the sample input for MPC-24.

3.2 MPC-68 criticality

The second sample input file shows criticality calculation of MPC-68 containing 68 fresh fuel assemblies of GE 8X8C04.The GE 8X8C04 fuel assembly has 62 U-235 fuel rods with 4.2 wt% of enrichment and active fuel length of 150 inches. Table II shows results from the SAR and our MCNP5 benchmarking calculation.

Table II: Criticality calculation for the MPC-68 cask

	SAR result	MCNP5
k_{eff}	0.93070	0.92892
σ_c	0.00070	0.00067
$\alpha_c\sigma_c$	0.00140	0.00134
$\Delta k_b + \alpha_b\sigma_b$	0.00280	0.00280
$k_{eff}^{\max}$	0.93490	0.93306
$k_{eff}^{\max}$ difference (pcm)	184	

For the MPC-68, the calculated maximum k_{eff} value has a difference of 184 pcm from the SAR result, which is within 3σ; therefore, it is considered that the calculation of criticality safety is valid with the sample input for MPC-68 as well.

Consequently, all of our MCNP5-based maximum k_{eff} values are less than the SAR results as summarized in Tables I and II, all of our results are less than the criticality criterion of 0.95. The maximum k_{eff} differences may be due to differences in the code versions. MCNP5 is used in own calculations, whereas MCNP4a was used in the SAR. The two versions might have different systematic errors.

4. Conclusions

We performed criticality calculations of the HI-STAR 100 cask system by running the MCNP5 code. The safety analysis report (SAR) of the HI-STAR 100 cask system presents the MCNP4a result of criticality analysis in the fully flooded condition in which the multiplication factor would assume the highest value. By running the MCNP5 code, we obtained smaller values of the maximum k_{eff} than the results from the SAR and all of them are below the criticality criterion of 0.95.

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