Criticality and Its Uncertainty Analysis of Spent Fuel Storage Rack for Research Reactor

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1. Introduction

For evaluating the criticality safety of spent fuel storage rack in an open pool type research reactor, a permissible upper limit of criticality should be determined. It can be estimated from the criticality upper limit presented by the regulatory guide and an uncertainty of criticality calculation.

In this paper, criticalities for spent fuel storage rack are carried out at various conditions. The calculation uncertainty of MCNP system is evaluated from the calculation results for the benchmark experiments. Then, the upper limit of criticality is determined from the uncertainties and the calculated criticality of the spent fuel storage rack is evaluated.

2. Criticality Calculation of Storage Rack

The criticality of spent fuel storage rack in a storage pool takes into consideration the following conservative conditions which are based on the U.S. NRC [1] regulatory guide for spent fuel storage pool.

i. All fuels stored in storage pool are fresh.
ii. Except the cell tube of storage rack, the structures such as storage lattice and frame are ignored.
iii. The case that the pool water temperature increases over 100 °C should be considered.
iv. The fuel assemblies are infinitely arranged in horizontal and axial directions.

For analyzing the uncertainty in the criticality calculation of spent fuel storage, the calculations are carried out under the four conditions of storage pool as the followings.

2.1 Normal pool water temperature condition

The pool water temperature is set to 40 °C as the normal condition case. The inner diameter of cell tube inside storage rack is 115.0 mm. As the thickness of cell tube is determined by 3 mm, the outer diameter of cell tube is set as 121.0 mm in all calculations. For the purpose of an efficient and conservative calculation, only one fuel assembly with a reflective boundary condition is modeled.

2.2 Increased pool water temperature condition

The case of pool water temperature at 100 °C is selected and evaluated for the abnormal condition of storage pool. Except the water temperature, all parameters are the same as those of the normal condition.

2.3 Fuel drop accident

The accident that a fuel assembly is horizontally dropped on the top of the storage rack filled with fuel assemblies, is considered for the criticality safety. For selecting the most conservative case, a few cases are analyzed. The results show that the worst case among them is that the both sides of the dropped fuel exactly coincide with those of the underlying the fuel. It is noted that a reflective boundary condition is assumed in the axial boundary for the most conservative condition.

2.4 Eccentric insertion

If four neighboring fuel assemblies would lean to the center edge of four storage lattices, the criticality might increase due to a positive reactivity. Therefore, this eccentric insertion should be considered for the criticality safety. In this study, fuel assemblies are moved 2.81 mm to the center of four cell tubes, and then the minimum distance from the edge of fuel assembly to the cell tube is set as 0.1 mm because the inner radius of cell tube is 57.5 mm and the circumradius of fuel assembly is 54.59 mm.

All calculations are performed using MCNP5 code with ENDF/B-VII library. The number of the history generation is total 1,000,000 through 10,000 particles/cycle and 100 active cycles with 50 inactive cycles, and the standard deviation results in about 0.00025. The calculated criticality is summarized in Table I.

Table I: Results of Criticality Calculation

Case	K_{inf}	*SD*	*ΔK*
Normal Condition	0.74283	0.00022	-
Increased Pool Water	0.76065	0.00023	0.01782
FA Drop	0.75368	0.00023	0.01085
Eccentric Insertion	0.74328	0.00023	0.00045

3. Uncertainty Analysis

3.1 Uncertainty of MCNP Code System in Criticality Calculation

The bias and the uncertainty of MCNP in criticality calculation are evaluated from the simulations of benchmark experiments presented at NEA NSC [2].

Prior to the bias evaluation, it should be analyzed whether there is a linear correlation between independent variable such as enrichment or lattice pitch and dependent variable such(?) as the difference of criticality. By selecting enrichment as an independent variable, in this study, 19 benchmark problems are analyzed and the results are depicted in Figure 1. It shows that there is no noticeable correlation between two variables resulting from t-test.

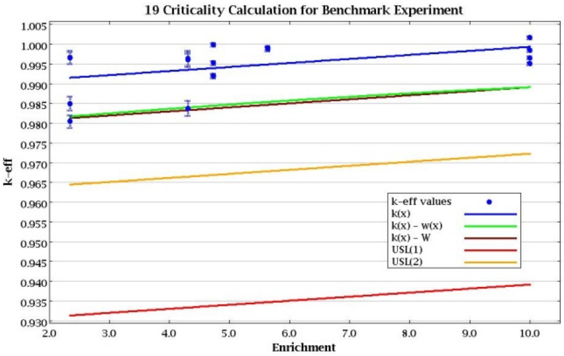

Fig. 1 Correlation between the criticality and the enrichment for benchmark experiments

121 benchmark problems are selected for uncertainty evaluation. The average value of the criticality bias ($\Delta k = k_{eff}^{Experiment} - k_{eff}^{MCNP}$) is 0.00510 and the standard deviation is 0.00564. From the t-distribution, the t value is 1.98 at 95% confidence interval and 120 degrees of freedom. Therefore, the bias in the criticality calculation ranges from 0.00408 to 0.00612 by the following equation.

$$0.00510 \pm 1.98 \times \frac{0.00564}{\sqrt{120}} = 0.00408, 0.00612 \qquad (1)$$

Thus, the maximum bias, 0.00612, is determined with a conservative view that MCNP underestimates.

3.2 Uncertainty of Criticality with the Variance of Storage Pool Condition

As described in the previous section, the criticality calculations by MCNP are performed under the abnormal conditions of storage pool. As shown in Table I, the reactivity increases by 17.82 *mk* in the case of the pool temperature at 100 °C and is predicted to be 10.85 *mk* higher than that in the normal condition for the case of a fuel assembly drop. When four neighboring fuel assemblies are inserted eccentrically toward the center edge of the storage lattices, the criticality increases by 0.45 *mk*.

3.3 Uncertainty of Criticality by the Cell Tube Thickness

As a manufacturing tolerance of the cell tube thickness is known as ±0.02 mm [3], the variance of the cell tube thickness may affect the criticality. Therefore, the criticality calculations are carried out for the cell tube thicknesses of 2.9 mm and 3.1 mm. The uncertainty based on the variation of the cell tube thickness is estimated to 0.00429.

3.4 Uncertainty Evaluation of Spent Fuel Storage Rack in Storage Pool

Consequently, the total bias is 0.03524 as shown in Table II and the total uncertainty is determined as $0.03524 \pm 1.96 \times 0.00709 = 0.02134, 0.04914$ at 95% confidence interval. The upper limit of criticality calculation by MCNP becomes 0.85086 because the upper subcriticality limit of storage pool given in the guideline for non-power reactors [4] is 0.90 and the total uncertainty, 0.04914, is subtracted for a conservative evaluation.

Table II: Bias and Uncertainty of Criticality Calculation

Case	Bias	Uncertainty
MCNP Calculation System	0.00612	0.00564
MCNP Standard Deviation		0.00023
Cell Tube Thickness Uncertainty		0.00429
Increased Pool Water	0.01782	
FA Drop	0.01085	
Eccentric Insertion	0.00045	
Total	0.03524	0.00709

4. Conclusions

In order to evaluate the criticality safety of spent fuel storage rack in an open pool type research reactor, criticality calculations for spent fuel storage rack are carried out at four conditions of normal pool water, increased pool water, fuel assembly drop, and eccentric insertion. The calculation uncertainty of MCNP system is evaluated using the calculation results for the benchmark experiments.

Considering biases and uncertainties in MCNP code system, the abnormal storage pool condition and manufacturing tolerance of the cell tube thickness, the total uncertainty is determined to 0.04914. The upper limit of criticality by MCNP calculation becomes 0.85086. The calculated criticality of the spent fuel storage rack, 0.74283, satisfies the upper limit of criticality.

REFERENCES

[1] "Spent Fuel Storage Facility Design Basis," proposed revision to Regulatory Guide 1.13 (Draft CE 913-5) Dec. 1981.

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[4] NUREG-1537, Part 2, Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors, Standard Review Plan and Acceptance Criteria, U.S.NRC, February 1996.