Criticality Analysis for SMART Fuel Storage

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1. Introduction

The SMART (System-integrated Modular Advanced ReacTor) is an integral type of small modular reactor (SMR) with 365 MW_{th} which was developed by Korea Atomic Energy Research Institute (KAERI).

In this paper, the criticality in fresh and spent fuel storage, and fuel handling system of SMART are evaluated using MCNP6 with ENDF/B-VII library code [1]. The bias and uncertainty calculation is also evaluated from the calculation of the benchmark experiments by MCNP. Then, the final criticalities are obtained from the above evaluation values.

2. Criticality Analysis of Fuel Storage

For evaluating the criticality safety assessment of fuel storage in typical reactor, a permissible upper limit of criticality shall be determined. As regulatory guide states, the criticality for fresh and spent fuel, and fuel handling system shall not be exceed 0.95 or 0.98 limits [2].

In order to perform the criticality analysis evaluation, the effective multiplication factor (k_{eff}) can be calculated through various critical experiments and the following equation [3].

$$k_{eff} = k_{cal} + \Delta k_{bias} + \Delta k_{uncertainty}$$

where,

k_{cal} : Calculated nominal value of the effective multiplication factor

Δk_{bias} : Bias in criticality analysis methodology

$\Delta k_{uncertainty}$: Uncertainty due to design variables and calculation

In order to verify the validity of the criticality analysis method, bias and uncertainty calculation shall be considered with regarding criticality calculations. For the criticality calculation for fresh fuel storage, optimum moderation condition and flooding condition with mechanical tolerance and design parameters shall be considered. For spent fuel storage, criticality of damaged spent fuel storage and postulated accident condition shall be considered, and criticality of fuel handling system shall be considered for criticality evaluation for fuel storage.

The MCNP6 with ENDF/B-VII library code is computerized analysis code based on Monte Carlo method, which includes statistical uncertainty always as calculation results are distribute in accordance with the standard normal distribution of true value. Statistical uncertainty is given in the MCNP output file.

2.1 Bias and Uncertainty Evaluation

For the criticality bias calculation, criticality experiments using UO_2 fuel in "International Handbook of Evaluated Criticality Safety Benchmark Experiments" [4] had been selected due to appropriate consideration of characteristics for performing criticality analysis on the typical PWR fuel pool. For the selection, the characteristics of light water reactor fuel storage facilities had been considered as follows:

- Fuel (UO_2) is mounted inside the cladding as a pellet type.
- The alignment of fuel rod is composed of a square lattice structure.
- Water is present as a moderator.
- Neutron absorber or stainless steel plate is present between fuel assemblies.
- Fission occurs by thermal neutron mainly.

Bias for the criticality analysis methodology is a mean value of difference between 1 and the ratio of calculated effective multiplication factor to the value of the effective multiplication factor of the critical experiment. The bias value is calculated as following equation [5].

$$\Delta k_{bias,i} = \frac{k_{exp,i} - k_{cal,i}}{k_{exp,i}}$$

$$\Delta k_{bias,avg} = \frac{1}{n} \sum_{i=1}^{n} \Delta k_{bias,i}$$

Also, a standard deviation of the bias calculation value is obtained using the following equation.

$$\sigma(\Delta k_{bias,avg}) = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (\Delta k_{bias,i} - \Delta k_{bias,avg})^2}$$

304 selected benchmark cases are calculated for bias and uncertainty evaluation. Mean of k_{eff} is calculated as 0.99748 and standard deviation (σ) is calculated as 0.005167. The 2σ at 95% probability with 95% confidence interval is calculated as 0.01086 in which the conservative tolerance limit factor is applied [6]. The results is shown in Table 1.

Table 1 Bias and Uncertainty of MCNP6

	k_{eff}
Mean effective multiplication factor	0.99748
Bias (1-k_{cal})	+0.002515
Uncertainty (2σ)	0.01086

2.2 Fresh Fuel Storage

A dry condition of the fresh fuel storage may be changed depend on the outer condition. Thus, the criticality of the fresh fuel storage shall be evaluated considering the water density in actual SMART fresh fuel storage model shown in Figure 1. By changing the water density from 0.01 g/cc to 1.0 g/cc, optimum moderation condition shall be evaluated. The criticality of optimum moderation condition shall not be exceed 0.98 [2].

The evaluation of flooding condition is performed for the criticality with mechanical tolerance and design parameters in condition of optimum moderation. Mechanical tolerance and design parameters are errors that occur during the designing and manufacturing fuel storage rack, and loading the fuel assemblies. These factors can increase the criticality such as fuel assembly misloading case which is contacted with the corners of the storage cells have high reactivity position. In order to evaluate the criticality due to the mechanical tolerances and design parameters, the calculation results of each considerations with lower than the result of reference model are excluded. From that result, the final result is calculated using the following equation:

$$\Delta k_{error} = \sqrt{\sum_{i=1}^{n}(k_{error,i} - k_{nominal})^2}$$

where $k_{error,i}$ refers to a calculation result of k_{eff} according to input parameter i. The criticality of flooding condition shall not be exceed 0.95 [2].

For criticality of fresh fuel storage, the calculation of optimum moderation condition in considering with water density from 0.01 g/cm³ to 1.00 g/cm³ and the calculation of flooding condition with mechanical tolerance and design parameters in condition of optimum moderation are evaluated in SMART actual model. For criticality of optimum moderation condition, the maximum effective multiplication factor value is evaluated when the water density is 1.00 g/cm³ which is 0.929966 as shown in Figure 2. For flooding condition, effective multiplication factor value is calculated as 0.933564. All the results for fresh fuel storage are shown in Table 2.
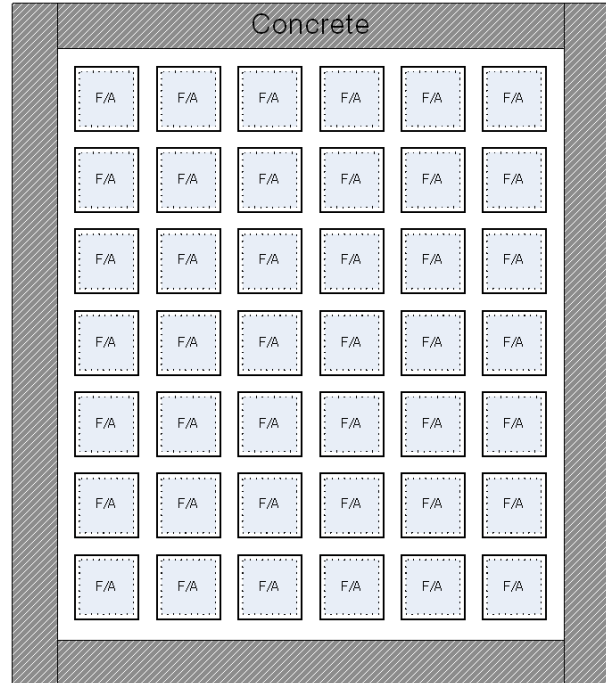

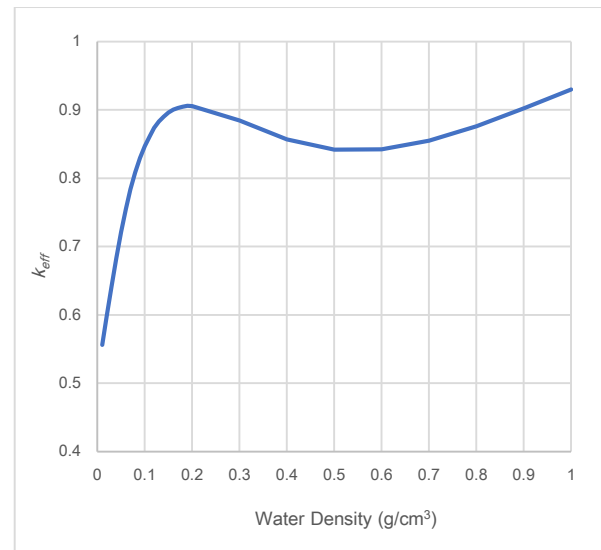Figure 1 Structure of SMART Fresh Fuel Storage

Figure 2 Criticality for Various Water Densities

Table 2 Criticality of Fresh Fuel Storage

	k_{eff}
Optimum moderation condition (ρ_{water}=1.0 g/cm³)	0.929966
Flooding condition with mechanical tolerance and design parameters	0.933564

2.3 Spent Fuel Storage

To evaluate the criticality of SMART spent fuel storage, damaged fuels are assumed to be store in storage cell area as shown in Figure 3. The criticality of damaged spent fuel storage shall not be exceed 0.95 [2].

Postulated accident condition shall be considered for spent fuel design. The mal-positioned condition that can cause criticality accidents in the spent fuel storage in the SMART are as follows:

- Inflow of demineralized water of cooling water into the pool
- Misloading fresh fuel
- Drop of fuel in the upper side of the spent fuel storage

For accidents of inflow of demineralized water into cooling water, all calculations are done assuming demineralized water so the accidents are removed from postulated accidents. Since all spent fuels are assumed as fresh fuel in previous calculations, misloading fresh fuel is excluded from the postulated accidents. Accordingly, only the postulated accident scenario where fuel assembly is dropped and positioned at the upper part of the storage cell in the middle of a loading process in the spent fuel storage is selected and evaluated as a postulated accident. The criticality of postulated condition shall not be exceed 0.95 [2].

For spent fuel storage, the criticalities of the normal and abnormal condition are calculated in infinite array model. The effective multiplication factor due to the reference model of spent fuel storage cell with mechanical tolerance and design parameters in normal condition is 0.92678. In condition of withdrawn spent fuel storage including the damaged fuel storage cells is calculated as 0.92249 ± 0.00010. The criticality at the time of drop accident of the spent fuel rack is calculated as 0.78132 ± 0.00016 at 1500 ppm and 0.73703 ± 0.00009 at 2000 ppm. All the results for spent fuel storage are summarized in Table 3.
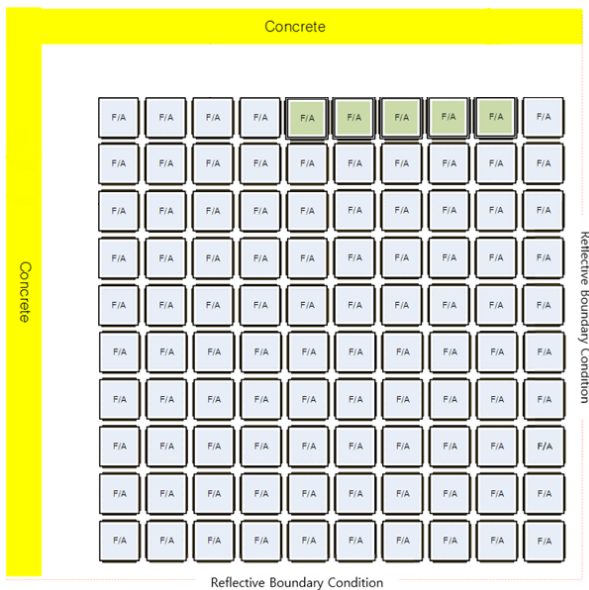
Table 3 Criticality of Spent Fuel Storage

Case			k_{eff}
Normal condition			0.92678
Abnormal condition	Damaged fuel		0.92249 ± 0.00010
	Mal-positioned	1500 ppm	0.78132 ± 0.00016
		2000 ppm	0.73703 ± 0.00009

2.4 Fuel Handling System

A length of the fuel assembly is assumed to be calculated using the real geometric structure parameters up to the active fuel length and other upper and lower structures are replaced with demineralized water and replace the structure except fuel assembly in mast structure with water for the convenience of calculation. The criticality of fuel handling system shall not be exceed 0.95 [2].

For fuel handling system, the criticality is calculated with mechanical tolerance and design parameters in infinite array model and the result is 0.94929 as shown in Table 4.

Table 4 Criticality of Fueling Handling System

	k_{eff}
Fuel handling system with mechanical tolerance and design parameters	0.94929

3. Conclusion

This paper shows that the criticality evaluation of fresh and spent fuel storage, and fuel handling system for SMART following the design model for safety assessment. To minimize the uncertainty of the criticality evaluation results, furthermore, bias and uncertainty due to criticality evaluation from MCNP code are evaluated. All criticality calculations for fresh and spent fuel storage, and fuel handling system of SMART are within the limits not exceeding.

Figure 3 Structure of Damaged Spent Fuel Storage Rack

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