Criticality Safety Calculation and Analysis for NPP Transportation of Fuel Assemblies

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Abstract: Nuclear criticality safety was calculated by MC code for transportation activity of fuel assemblies to Sanmen Nuclear Power Plant. Calculation result shows that the transportation of fuel assemblies meets the corresponding criticality safety requirements. In the calculation, eight criticality benchmark experiments for Low-Enriched Uranium rods lattice from NUREG/CR-6361 of the U.S. NRC was selected, and was validated calculation by SuperMC. Thereby, the result of criticality calculation for transportation of fuel assemblies with SuperMC code becomes more reliable.

1 INTRODUCTION

Nuclear criticality safety is an important issue in the storage and transportation of fissile materials. Regulations for the Safe Transport of Radioactive Material (GB11806-2019) has clear requirements for nuclear criticality safety in the transportation of fissile materials, such as fuel assemblies, etc. The IAEA SSR6 also provides a detailed introduction to the criticality safety assessment, including the criticality safety analysis model, method, calculation and experiments (SSG, 2012).

The Monte Carlo method can better model the geometric structure in the criticality safety analysis and is widely used. However, when using the MC program to calculate the criticality safety, various uncertainties must be considered to give the bias of the program, such as model size, fuel enrichment, section data, calculation method, etc. (LI, 2019) In addition, since it is necessary to model and write input files when using MC program for criticality safety calculation, the calculation results of the program may vary from person to person. Therefore, when using the MC program for critical safety calculation, the bias of the program must be determined first.

2 CALCULATION PROGRAM AND DETERMINATION OF SUBCRITICAL LIMIT

2.1 Calculation Program

This project is supported by Super Monte Carlo Program for Nuclear and Radiation Simulation, named SuperMC, which is developed by Institute of Nuclear Energy Safety Technology, Chinese Academy of Science/the FDS Team. SuperMC is a general, intelligent, accurate and precise simulation software system for the nuclear design and safety evaluation of nuclear system (WU, 2009; WU, 2015).

2.2 Subcriticality Benchmark Experiment and Simulation Calculation

This paper selects a group of eight subcriticality benchmark experiments in Criticality Benchmark Guide for Light-Water-Reactor Fuel in Transportation and Storage Packages (NUREG/CR-6361) (Lichtenwalter, 1997) of the US Nuclear Regulatory Commission, and Dissolution and Storage Experimental Program with UO_2 Rods (Manaranche, 1979), which are ANS33AL1, ANS33AL3, ANS33EB1, ANS33EB2, ANS33EP1, ANS33EP2, ANS33SLG and ANS33STY respectively. Fuel assembly dimensions, fuel rod characteristics, material parameters and criticality data are described in detail in the literature.

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Table 1: Simulation Results of Subcriticality Benchmark Test by SuperMC.

Subcriticality benchmark experiment	k_{eff}±σ
ANS33AL1	1.00071±0.00186
ANS33AL3	0.99958±0.00169
ANS33EB1	0.99835±0.00173
ANS33EB2	1.00496±0.00162
ANS33EP1	1.00121±0.00180
ANS33EP2	0.99939±0.00183
ANS33SLG	0.99769±0.00166
ANS33STY	0.99510±0.00169

For fuel rods, the bottom end plug is simulated as an aluminum cylinder with a diameter of 0.94 cm and the top plug is 1.3 cm. The spring is not simulated but replaced by air. The stainless steel fuel grid with a thickness of 0.25cm at the bottom is also not considered.

Use SuperMC to calculate these criticality benchmark models, and the calculation results are listed in Table 1. The cross section data used in the program calculation is mainly from the endf60 continuous energy neutron cross section library, and 250 iterations are used in the program calculation, and the results of the first 50 iterations with poor statistics are omitted. The average value of the results of the last 200 iterations is used, and the number of particles simulated in each iteration is 1000.

2.3 Analysis of Simulation Results

The simulation results of the eight critical benchmark experiments using SuperMC program are very close to the test results, and more close to the critical value 1.0, with the maximum deviation of 0.496% and the minimum deviation of 0.042%. It can be seen from Table 1 that the average deviation $\bar{b}$ and the calculated standard deviation σ of the SuperMC program for the calculated value of the critical benchmark simulation are:

$$\bar{b} = \frac{\sum_{i=1}^{9} \left| k_{eff(i)} - 1 \right|}{8} \approx 0.00210 \qquad (1)$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{9} \left(k_{eff(i)} - 1 \right)^2}{8}} \approx 0.00272 \qquad (2)$$

Then consider various uncertainties of the program (including fuel enrichment, model geometry, material cross-section data, experimental data, calculation methods, etc.), conservatively add 3 times of the standard deviation σ to the above average deviation $\bar{b}$, that is, the bias of the SuperMC program σ_b is

$$\sigma_b = \bar{b} + 3\sigma \approx 0.0103 \qquad (3)$$

3 NUCLEAR CRITICALITY SAFETY CALCULATION FOR FUEL ASSEMBLY TRANSPORTATION

3.1 Description of Transport Container

The shape of PWR fuel assembly transport container is a tubular structure, mainly including two parts: outer cylinder and inner cylinder. The structure is shown in Figure 1.

(1) Outer cylinder

The outer cylinder consists of an upper cover and a base. It is a "steel foam plastic steel" laminated structure composed of an austenitic stainless steel shell, an inner shell and a rigid polyurethane foam plastic between two shells. The upper cover can be opened or removed, and the base is fixed on a forklift bracket. The base of the outer cylinder is connected with the hinges on both sides by 24 hexagon bolts, and the upper cover is also connected with the hinges by 24 bolts. When all 48 bolts are fastened, the upper cover and base are fixed together. When the 12 bolts connecting the upper cover and hinge on one side are removed, the upper cover connected through the hinge on the other side can be just like a door. Acrylic glass fiber sealing gasket is set between the joint surface of upper cover and base to prevent rainwater from entering the package. There is no pressure seal design between the transport container package and the surrounding environment, so there will be no differential pressure in the package.

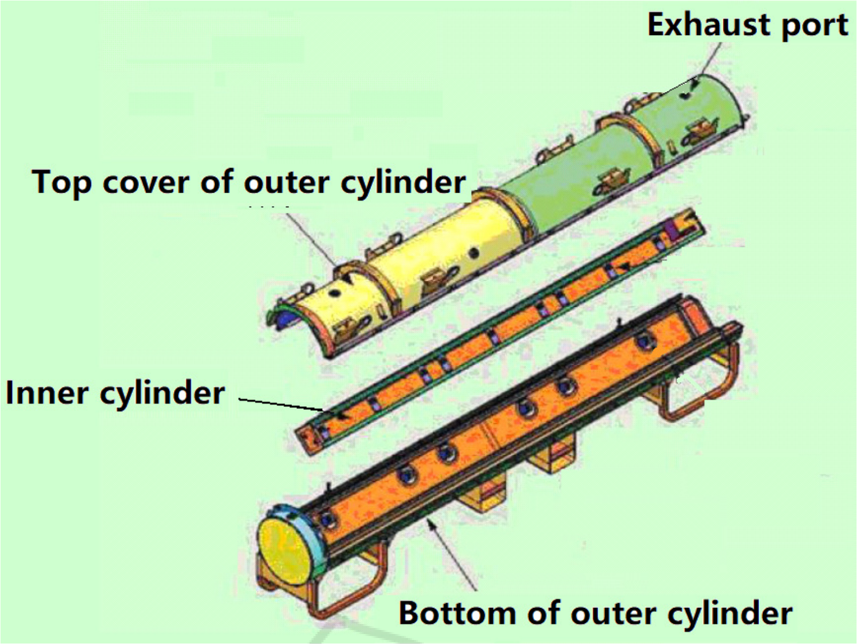

Figure 1: Fuel Assembly Shipping Container Component Drawing.

The outer shell of the outer cylinder is used to bear the structural strength of the container, and the lower part is designed with a forklift platform to lift, stack and tie down the container during transportation; The foam plastic of the outer cylinder interlayer is used for heat insulation and impact protection. Some polyethylene blocks are attached to the inner shell of the outer cylinder for critical safety; The two ends of the outer cylinder are equipped with shock absorbers, which are made of 20 pcf polyurethane foam covered with stainless steel leather.

(2) Inner Cylinder

The inner cylinder is a rectangular box composed of an aluminum V-shaped positioning plate, two aluminum plate doors, bottom and top plates, and a multi-point cam hinge and latch device. It plays the role of protecting the built-in fuel assembly structurally; The V-shaped locating plate and two aluminum doors are connected by continuous (11 cams) hinges. One aluminum door is equipped with a cam lock plate, which is locked with the other door by turning at right angles; The fixing structure of the top plate of the inner cylinder and the inner cylinder wall is designed with flat head hexagon hole screws, nuts and recessed seams. The bottom plate is also fixed to the inner cylinder through screws, and can be closed by connecting the nut and groove with the inner shell door. The inner surface of the inner cylinder is attached with a neutron absorption plate, which is installed on the inner surface along the full length of the four sides of the inner cylinder and is fixed on the inner wall with threaded fasteners.

The inner cylinder is also a part of the container restraint system, which can protect and constrain the fuel assembly under different transportation conditions. A rubber pad is set on the inner axial position of the inner cylinder door to constrain the lateral movement of the assembly. The top of the inner cylinder is equipped with an adjustable thread clamping component, which can provide the top axial restraint for the fuel assembly or the rod tube. When the fuel assembly is placed in it, additional restraint devices are added to fix it.

3.2 Fuel Assembly

PWR new fuel assembly consists of the fuel rod and fuel assembly skeleton arranged in a 17×17 square shape. The fuel assembly skeleton comprises an upper tube socket, a lower tube socket, a grid, a guide tube and a neutron flux measuring tube. Each fuel assembly consists of 289 grid cells, 24 of which are occupied by the guide tube, one by the neutron flux measuring tube, and the remaining 264 are loaded into the fuel rod or the overall burnable poison rod. The fuel rod is loaded into the fuel assembly framework and clamped by the grid to keep it at the specified axial and radial positions, and the fuel rod is allowed to expand freely along the axial direction. Sufficient clearance shall be reserved between the end of fuel rod and upper and lower tube sockets to compensate for different thermal expansion and irradiation growth between fuel rod and guide tube. When the fuel assembly is loaded into the core, it is assembled by the locating hole on the lower tube socket and the locating pin on the lower plate of the core to make it stand upright in the core. When the upper core plate is in place, press down the four groups of plate compression springs of the upper tube socket to provide enough compression force to position the fuel assembly on the designated position of the core, and it will not move upward under hydraulic scouring. The axial load applied on the fuel assembly and the weight of the fuel assembly are transferred to the lower plate of the core through the guide tube and the lower tube socket; The lateral load applied to the fuel assembly is transferred to the core support structure through the locating pins on the upper and lower core plates. See Table 2 for specific parameters.

3.3 Criticality Calculation Model

The calculation model includes two models: single package and infinite package array. Some conservative assumptions were adopted in the establishment of the critical safety calculation model, and the following conditions were mainly considered in the calculation:

(1) Under normal transportation conditions, there will be no water in the transport container;

(2) Under accident conditions, all the spaces inside the transport container are filled with water;

(3) The maximum 235U enrichment of fuel for shipment is 5% and UO2 density is 10.96 g/cm3;

(4) A 30 cm thick water reflecting layer is falsely set outside the transport container;

(5) The neutron poison plate is modeled according to 75% of the actual density of boron aluminum material, 1.942 g/cm3;

Table 2: Main parameters of fuel assembly.

component	Main parameters		
Fuel pellet	Material		Uranium dioxide ceramics
	Maximum ^{235}U enrichment(%)		4.80
	Diameter (mm)	Outer diameter (mm)	8.19
		inner diameter (mm)	3.94
	Length(mm)	Normal pellet	9.83
		Axial regeneration zone pellet	12.70
	Pellet density(g/cm^3)		10.41
Fuel rod	Cladding material		ZIRLO
	Rod length(mm)		4583.20
	Outer diameter (mm)		9.50
	Cladding wall thickness(mm)		0.57
Fuel assembly	Arrangement form		17×17 square
	Number of cells		289.00
	Number of fuel rods		264.00
	Fuel rod center distance (mm)		12.60
	Transverse overall dimension (mm)		213.97×213.97
	Total length of assembly (mm)		4798.70
	Height of active segment (mm)		4267.20
	Total weight of single component (kg)		794
	Metal uranium weight of single component (kg)		541

Table 3: Main materials and parameters.

Material	Chemical composition and corresponding atomic density(10^{24}/cm^3)	density(g/cm^3)
UO_2	U-238(2.32E-2) U-235(1.24E-3) O(4.89E-2)	10.96
Water	H(6.68E-2) O(3.34E-2)	1.00
Boron aluminum material	B-10(4.78E-3) B-11(1.94E-2) C(6.04E-3) AL(4.32E-2)	2.59
Polyethylene	C(3.95E-2) H(7.91E-2)	0.92
Foam	O(9.65E-4 H(9.57E-3) O(5.63E-3) N(2.76E-4)	0.16
Al	100%	2.70
Fe	100%	7.94
Zr	100%	6.56

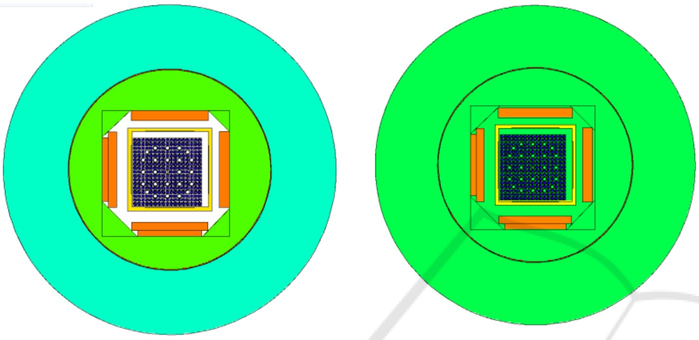

Figure 2: Model of single package under normal and accident conditions.

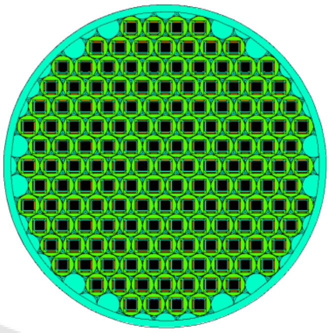

Figure 3: Cross section of 151 packages array.

(6) The polyethylene material is modeled according to 90% of the actual density, 0.828 g/cm3;

(7) In order to simplify the calculation model, the positioning grid, upper and lower tube sockets and damping frame are not considered in the fuel assembly.

The main materials and corresponding parameters used in the model are listed in Table 3. Under normal and accident conditions established by SuperMC, when the outermost layer of the package is set as specular reflection. The section of the calculation model is shown in Figure 3.

3.4 Calculation Results and Analysis

The calculation results are listed in Table 4.

Since the enrichment of ^{235}U in the simulated fuel rod UO_2 pellet is 5%, the actual enrichment is less than 4.8%, the UO_2 density selected for calculation is conservative. It can be seen from Table 4 that under accident conditions, the keff value of the infinite cargo package array first decreases, then increases, and then decreases with the decrease of water density. When the water density is 1.0 g/cm^3, the keff has a maximum value.

4 CONCLUSION

In this paper, the Monte Carlo software SuperMC is used to analyze the critical safety performance of new fuel transportation containers under normal transportation conditions and transportation accidents. Based on the characteristics of new fuel and possible accident scenarios, eight benchmark test cases that meet the requirements are selected for verification. According to the statistical analysis of benchmark test calculation results, the bias of the SuperMC is 0.0103.

For a single package, water will not enter the package under normal transportation conditions, and the maximum k_{eff} value after considering 3 times of standard deviation and the standard deviation of the critical calculation program is 0.22733; The maximum k_{eff} value of water entering the internal clearance of the cargo package under accident conditions is 0.85,704 after considering 3 times of the standard deviation and the standard deviation of the critical calculation program, which belongs to subcritical.

Table 4: The calculation case and results of criticality safety.

Calculation conditions	Water density (g/cm^3)	k_{eff}	σ	k_{eff}+3σ	$k_{eff}+3\sigma+\sigma_b$
Normal conditions of single package	1.0	0.2159	0.00039	0.21707	0.22733
Accident conditions of single package	1.0	0.84414	0.00088	0.84678	0.85704
Normal conditions of unlimited package array	1.0	0.27262	0.00049	0.27409	0.28435
Unlimited package array accident conditions	**1**	**0.89921**	**0.00088**	**0.90185**	**0.91211**
	0.995	0.89678	0.00084	0.8993	0.90956
	0.99	0.89381	0.00084	0.89633	0.90659
	0.98	0.88681	0.00079	0.88918	0.89944
	0.97	0.88395	0.00078	0.88629	0.89655
	0.96	0.87901	0.00086	0.88158	0.89184
	0.95	0.87456	0.00095	0.87741	0.88767
	0.94	0.86960	0.00078	0.87194	0.8822
	0.93	0.86550	0.0008	0.8679	0.87816
	0.92	0.86103	0.00082	0.86346	0.87372
	0.91	0.85311	0.00079	0.85547	0.86573
	0.9	0.84866	0.00087	0.85127	0.86153
	0.8	0.79102	0.00083	0.79351	0.80377
	0.7	0.72706	0.00084	0.72958	0.73984
	0.6	0.65704	0.00085	0.65959	0.66985
	0.5	0.58353	0.00079	0.5859	0.59616
	0.4	0.50542	0.00071	0.50755	0.51781
	0.3	0.43179	0.00057	0.4335	0.44376
	0.2	0.37139	0.00053	0.37298	0.38324
	0.1	0.33845	0.0005	0.33995	0.35021

Under normal transportation conditions of 151 cargo bag arrays, the value of k_{eff} is 0.28435, Under accident conditions k_{eff} is 0.91211, which both are lower than 0.95，the limit of allowed by regulations. Nuclear criticality safety of new fuel assembly transportation activities is guaranteed.

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