ASSESSMENT OF CRITICALITY SAFETY FOR SPENT FUEL ELEMENTS IN OPEN POOL TYPE STORAGE

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Abstract

Storage of spent fuel elements needs a previous calculation to ensure verifying the criteria of storage from the nuclear criticality point of view. So, arrangements of spent fuel elements in the storage must result in a configuration characterized by an effective multiplication factor (k-eff) lower than 0.85. The spent fuel elements storage facility is an open pool connected with the main pool of the reactor via a transfer channel to facilitate transport of the irradiated fuel elements under water surface to assure a high radiological safety. The fuel element is a plate type for the material testing reactor (MTR), U_3O_8 fuel with enrichment of 19.97 wt% in ^{235}U, in a matrix of Al. The storage pool was designed to store around 800 spent fuel elements as a temporary stage before transporting to a permanent storage. Basket and pool models, loaded with fresh fuel elements, were used in KENO-VI criticality code included in SCALE6.1 system, for k-eff estimation during normal storage condition as well as in a potential water-drop accident. TRITON and KENO-VI sequence from SCALE6.1 system was applied to determine the k-eff for the basket and pool, loaded with spent fuel elements, during the normal and the accidental considered conditions. All the spent fuel elements were irradiated in the reactor core, at 22 MW power, being discharged after the maximum burn up is reached. k-eff values shown a good agreement with previous calculations performed using MCNP5 code.

Keywords: *KENO-VI code, TRITON code, Nuclear criticality, Spent fuel storage, Nuclear fuel burn-up, Effective multiplication factor*

Introduction

Nuclear criticality is one of the safety conditions that must be evaluated during storage of spent fuel elements. Spent fuel storage is an open pool type facility connected with main pool of the reactor through a transfer channel to facilitate transporting the irradiated fuel elements with the minimal radiological risk.

The Egyptian reactor was designed to operate at 22 MW full power level, continuously, for a cycle of 19 days followed by 2 days in shutdown state for maintenance and refuelling [1]. The storage pool is a stainless steel cylinder having 3.8 m in diameter and 7.5 m in high, provided with a cooling system to avoid fuel element overheating during storage. It was also provided with a water treatment system to maintain the proper conductivity and the PH of the pool water. It is surrounded by a heavy concrete structure sufficient to assure radiological safety in the adjacent area.

The spent fuel elements in the storage pool are stored below the water surface, at a depth of 460 cm to maintain the dose rate in the area above the water surface lower than the permissible limit [2]. The storage pool was provided with stainless steel racks able of storing 200 baskets, each basket containing four fuel elements.

The effective multiplication factor (k-eff) resulting from the arrangement of fuel elements in the basket, and then on the racks, must be evaluated to ensure and verify the criteria of nuclear criticality during the storage (k-eff $\pm 2\sigma$) < 0.85 [3].

Conservatively, the effective multiplication constant would be first calculated considering fresh fuel elements, and then considering that all the fuel elements were irradiated till the maximum discharge burn-up (this representing the real case).

KENO-VI code included in SCALE6.1 system [4] was used to determine the k-eff for the basket and the storage pool loaded with fresh fuel elements. TRITON module and KENO-VI sequence from SCALE6.1 [5] were used to evaluate the k-eff for the basket and the storage pool loaded with spent fuel elements irradiated to the maximum discharge burn-up.

TRITON is a module for isotopic depletion calculation; KENO-VI is a module for criticality calculation. The nuclear data used in these simulations are based on ENDF/B-VII.0 238-group neutron library.

The k-eff was calculated for the basket and the storage pool models during the normal operation and accidental conditions. The accidental conditions might result from dropping of water level in the basket and in the storage pool due to loss of coolant accident (LOCA). Estimated k-eff would be compared with previous calculations, for the same conditions, using MCNP5 code [6].

Materials and Method

Description of spent fuel storage pool

The open pool storage is a cylinder of 7.5 m in height and 3.8 m in diameter, made of stainless steel and surrounded by a heavy concrete structure to assure safe radiological conditions in radial direction. The storage pool contains dematerialized water which provides radiological shielding in vertical direction for workers located near the storage pool and in adjacent areas [1].

The spent fuel is stored on stainless steel racks submerged under the pool water, at a level of about 4.6 m in depth (thickness of the water layer above the top of stored fuel). The storage pool contains two storage racks and each rack has rectangular arrangement positions for the fuel elements, as shown in Fig.1 [2]. The first rack (lower rack) is located at the bottom of the pool, and when its full storage capacity is reached, the following spent fuel elements would be stored on the second rack (upper rack) located above the first one.

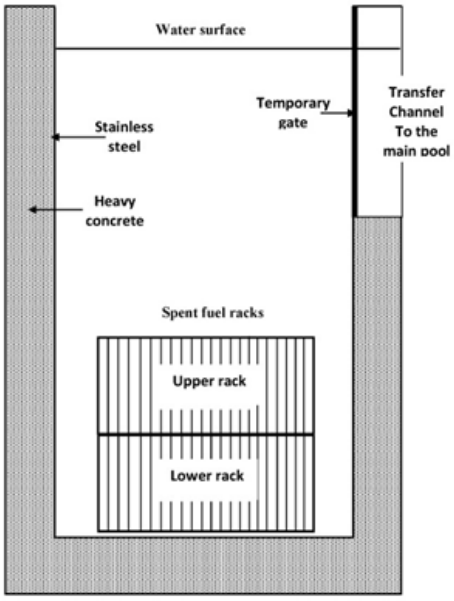


Fig.1. Vertical section in the spent fuel storage pool

The fuel elements are plate type elements for material testing reactor (MTR). Every fuel element is composed by 19 Aluminium fuel plates; each plate has a meat made by a dispersion of U_3O_8 particles with an enrichment of 19.97 wt% in ^{235}U, in a continuous matrix of pure Aluminium. The plates' active zone is 80 cm x 6.4 cm, with a meat thickness of 0.7 mm, and the Al cladding thickness of 0.4 mm. The coolant channel width is 2.7 mm. Each fuel plate contains 21.3 g of ^{235}U [7].

Spent fuel elements, removed from the core after irradiation, are placed on a storage position inside the reactor pool tank for two days. Then, the spent fuel elements are transferred under water through the transfer channel to the auxiliary pool (storage pool) to be stored on the storage racks. The storage racks can accommodate 200 metal baskets, each basket containing 4 spent fuel elements. The racks are made of stainless steel; the baskets' walls are made of Cadmium plates, cladded with stainless steel, as shown in Fig. 2 [6].

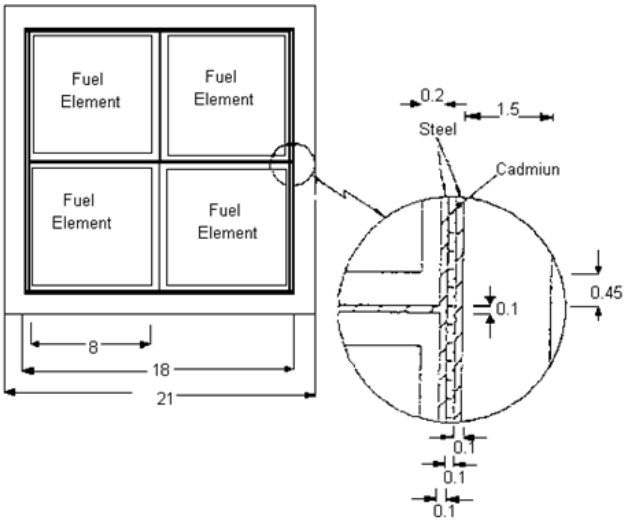


Fig.2. Fuel element basket - dimensions in cm

The SCALES models

SCALE/KENO-VI models were developed to simulate the basket and the storage pool, as shown in Figs. 3 and 4. The basket was considered as an arrangement unit in the spent fuel storage pool. The arrangement of the baskets in the storage pool would consider compliance with maximum allowed storage capacity. The multiplication factor would be calculated for the basket and the storage pool models using fresh and spent fuels. A white boundary was applied on the models for the conservative calculation of the multiplication factor.

The Basket Model

SCALE/KENO-VI model developed for the basket considers four fuel elements loaded with fresh fuel, the fuel elements active length being of 80 cm. It was used to calculate the multiplication factor (k-eff) based on ENDF/B-VII.0 238-group cross sections library. TRITON/KENO-VI sequence in SCALE6.1 was used to evaluate k-eff for the basket and storage pool loaded with spent fuel elements, discharged from the reactor core at maximum burnup degree. It was assumed that the fuel elements loaded in the basket were irradiated for a period of 275 days to achieve the maximum burnup (375 MW/TU).

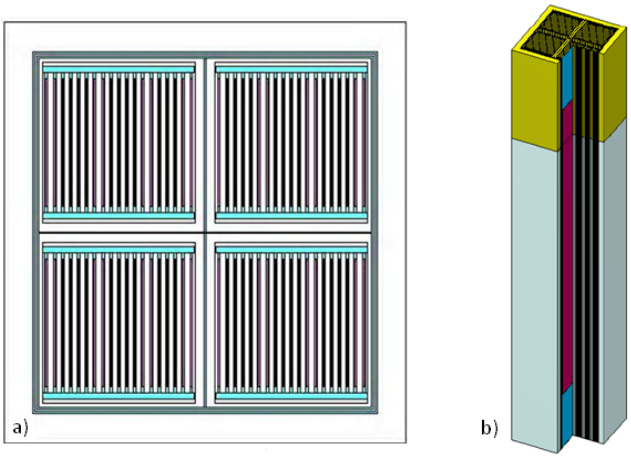


Fig.3. KENO3D model of
the basket loaded with fuel elements:
a) horizontal cross section; b) front right quarter cutaway

The two developed models for spent fuel basket and storage pool were applied both during normal operation and in accident conditions (water level dropping in the basket along up to 80 cm, active length of the fuel elements).

The Spent Fuel Pool Model

SCALE/KENO-VI model was developed for the spent fuel pool storage containing 200 baskets loaded with 800 fresh fuel elements to calculate a conservative value for k-eff using ENDF/B-VII.0 238-group cross sections library.

T6-DEPL (KENO-VI) sequence of TRITON was used for the spent fuel pool storage to evaluate the k-eff taking into consideration the fuel depletion. A continuous irradiation along a period of 275 days was considered for all fuel elements, until achieving a burnup degree of 375 MW/TU, which corresponds to the maximum burnup for irradiated fuel discharge.

Depletion calculations were performed by means of TRITON (T6-depl) sequence using KENO-VI criticality code for k-eff calculation. The two pool models were applied during normal operation and in the accidental drop of water level in the pool along up to 80 cm (active length of the fuel elements).

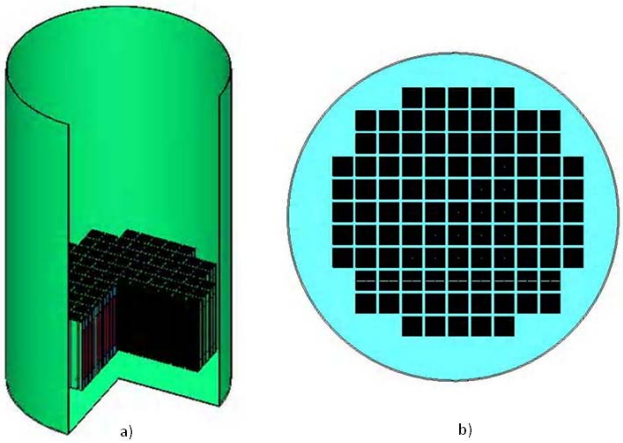


Fig.4. KENO3D model for the spent fuel storage pool loaded at full capacity:
a) front-right quarter cutaway; b) horizontal cross section

Results and Discussions

The k-eff calculations were carried out assuming that the basket with fuel elements was totally immersed under the pool water, in the normal condition for fresh and spent fuels. In the second case, k-eff was calculated assuming that water level drops in accidental conditions considering both fresh and spent fuels. For conservative calculations, a white boundary condition was applied both in the basket and the pool models.

Table 1 shows a comparison between the k-eff estimated for fresh and spent fuels in the basket, considering normal operation and accident conditions. For the basket loaded with fuel elements, both real and white boundaries were applied. In the mentioned table, the evolution of k-eff values as function of water level during the water dropping accident is also shown. For the k-eff values estimation, KENO-VI and MCNP5 codes have been used. For each of estimated k-eff value, the relative uncertainty is given.

During normal operating conditions, by applying white boundaries in the basket model, KENO-VI estimated k-eff values rise from 0.5464 to 0.7795 for fresh fuel, and from 0.4638 to 0.659 for spent fuel, respectively. For the same conditions, the k-eff values estimated by using MCNP5 code also rise when white boundaries are applied in the basket model, these values being lower than the KENO-VI estimated ones.

During accident conditions, estimated k-eff values rise as the depth of water level upon the fuel elements decreases, regardless the computer code used. Estimated k-eff values by using MCNP5 code are lower comparatively with the ones estimated by using KENO-VI code.

For the maximum dropping of the water level (80 cm), white boundaries applied in the basket model led to an increasing of k-eff estimated by KENO-VI from 0.5452 to 0.7835 for fresh fuel, and from 0.4629 to 0.6656 for spent fuel, respectively.

However, estimated k-eff values for normal operation and accident conditions were lower than 0.85 (limit value), so the criticality criteria condition for the spent fuel storage is met.

Table 1. Estimated k-eff values for the basket in normal operation and water drop accident conditions

Water level	SCALE/TRITON				MCNP5			
	White boundary		Real boundary		White boundary		Real boundary	
	Fresh fuel	Spent fuel	Fresh fuel	Spent fuel	Fresh fuel	Spent fuel	Fresh fuel	Spent fuel
Normal operation	0.7795 (0.0023)	0.6590 (0.0016)	0.5464 (0.0019)	0.4638 (0.0015)	0.76250 (0.00189)	0.66772 (0.00463)	0.53646 (0.00294)	0.46367 (0.00437)
80 cm	0.7835 (0.0018)	0.6656 (0.0016)	0.5452 (0.0016)	0.4629 (0.0016)	0.77212 (0.00179)	0.66984 (0.00466)	0.52889 (0.00294)	0.46089 (0.00100)
60 cm	0.7835 (0.0019)	0.6655 (0.0017)	0.5334 (0.0020)	0.4471 (0.0015)	0.76911 (0.00192)	0.66440 (0.00371)	0.51932 (0.00274)	0.44983 (0.00107)
40 cm	0.7746 (0.0019)	0.6518 (0.0015)	0.5062 (0.0019)	0.4271 (0.0015)	0.75192 (0.00163)	0.65451 (0.00421)	0.49364 (0.00324)	0.42848 (0.00102)
20 cm	0.7234 (0.0017)	0.6125 (0.0013)	0.4151 (0.0018)	0.3512 (0.0018)	0.70069 (0.00117)	0.60304 (0.00371)	0.40703 (0.00313)	0.34579 (0.00449)
10 cm	0.6484 (0.0016)	0.5476 (0.0013)	0.2837 (0.0013)	0.2380 (0.0012)	0.61608 (0.00115)	0.54368 (0.00357)	0.27138 (0.00495)	0.23010 (0.00359)

Table 2 shows estimated k-eff values for the storage pool loaded with fresh or spent fuel elements when applying white boundary in the pool model, during normal and accidental conditions. k-eff values evolution as function of the dropping of water level depth is also presented.

Table 2. Estimated k-eff for the storage pool in normal operation and water drop accident conditions

Water level	SCALE/TRITON		MCNP5	
	White boundary		White boundary	
	Fresh fuel	Spent fuel	Fresh fuel	Spent fuel
Normal operation	0.7713 (0.0021)	0.6538 (0.0017)	0.76142 (0.00120)	0.66362 (0.00214)
80 cm	0.7730 (0.0020)	0.6523 (0.0016)	0.76671 (0.00128)	0.66215 (0.00224)
60 cm	0.7616 (0.0016)	0.6460 (0.0015)	0.75372 (0.00115)	0.65678 (0.00109)
40 cm	0.7387 (0.0019)	0.6262 (0.0015)	0.72315 (0.00126)	0.63488 (0.00105)
20 cm	0.6649 (0.0018)	0.5639 (0.0019)	0.65422 (0.0016)	0.56997 (0.00105)
10 cm	0.5660 (0.0016)	0.4768 (0.0013)	0.55170 (0.00101)	0.48107 (0.00098)

During both normal operation and water drop accident conditions, estimated k-eff values for fresh fuel are higher than the ones corresponding to spent fuel, regardless the code used for calculations.
As the level of the water decreases, the estimated k-eff value become higher, regardless the computer code used for calculation. Thus, in the case of 80 cm water drop accident, the KENO-VI estimated k-eff is 0.7730 for fresh fuel and 0.6523 for spent fuel, respectively.

The estimated k-eff values, for normal and accidental conditions, were lower than 0.85, so they met criticality criteria condition for the spent fuel storage.

The k-eff values estimated by using both KENO-VI and MCNP5 codes would be achieved with the highest accuracy, as shown in the relative uncertainties values given between the brackets in Tables 1 and 2.

The calculations show a good agreement when comparing with previous calculations performed using MCNP5 code, as shown in Table 3.

Table 3. Relative differences in k-eff values for KENO-VI and MCNP5 comparison, [%]

Water level	Relative difference of k-eff [%]					
	Basket model				Pool model	
	White boundary		Real boundary		White boundary	
	Fresh fuel	Spent fuel	Fresh fuel	Spent fuel	Fresh fuel	Spent fuel
Normal operation	2.23	-1.31	1.85	0.03	1.30	-1.48
80 cm	1.47	-0.63	3.08	0.44	0.82	-1.49
60 cm	1.87	0.17	2.71	-0.61	1.05	-1.64
40 cm	3.02	-0.41	2.54	-0.32	2.15	-1.37
20 cm	3.24	1.57	1.98	1.56	1.63	-1.06
10 cm	5.25	0.72	4.54	3.43	2.59	-0.89

The small variations between the k-eff values estimated for these models in comparison with MCNP5 code results may be due to two reasons:
- using the ENDF/B-VII.0 238-group cross sections library for KENO-VI and TRITON codes comparatively with the continuous energy (CE) library used in MCNP5 model;
- using all the fission products and actinides in the k-eff calculations by means of KENO-VI and TRITON codes comparatively with using only the most effective isotopes, as results from ORIGEN2.1 code, in the MCNP5 model.

Conclusions

Evaluating the criticality safety criteria for a spent fuel storage pool is mandatory from the nuclear safety point of view. The storage pool used for temporary spent fuel storage is connected to the main pool via a transfer channel and it was provided with stainless steel racks with a total storage capacity of 800 spent fuel elements.

The fuel element is plate type for material testing reactor (MTR), being composed by 19 Al plates, each plate having a meat of U_3O_8 fuel enriched 19.97wt% in ^{235}U in a matrix of pure Al.

SCALE/KENO-VI and SCALE/TRITON/KENO-VI models were developed to evaluate the effective multiplication factor, k-eff, for fresh and spent fuels, in normal and accidental conditions by applying white boundary for conservative calculations.

For the basket model, k-eff would be 0.7795 and 0.659 for fresh and spent fuels, respectively, during normal operation conditions. For accidental water level drop, k-eff would range between 0.7835 and 0.478 for fresh fuel, and from 0.6656 to 0.4123 for spent fuel, depending on the water level.

For the storage pool model, k-eff would be 0.7713 and 0.6538 for fresh and spent fuels, respectively, during normal operation conditions. In case of accidental water level drop, k-eff would range between 0.7730 and 0.3413 for fresh fuel, and from 0.6523 to 0.29515 for spent fuel, depending on the water level.

A comparison was performed between the estimated k-eff values and previous k-eff calculated using MCNP5 code, and a good agreement was obtained, as shown in Table 3.

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