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Criticality calculations for the spent fuel storage pools for Etrr_1 and Etrr_2 reactors

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Abstract A criticality analysis of two spent fuel storage pools for Etrr_1 and Etrr_2 research reactors was performed. The multiplication factor for the pools was calculated as a function of relevant lattice physics parameters. Monte Carlo code MCNP-4A code was used in the criticality calculations. The results were compared with those given by CITATION code and the results obtained formerly during the design phase of the pools [9] with the MONK 6.3 code. Safety of the pools was confirmed.

Key words criticality safety • research reactors

Introduction

Safe and efficient storage of spent fuel elements is an important aspect of the safety and economy of nuclear reactors. In this paper the criticality of spent fuel storage pools for Etrr_1 and Etrr_2 Egyptian research reactors was studied primarily for operational conditions. Besides, several lattice parameters were varied to establish their influence on K_{eff}. In the following, the facilities will be referred to as Pool_1 and Pool_2, respectively.

In normal conditions the fuel elements are fully submerged in water and the water temperature is 20°C. In agreement with a common practice, the effect of water temperature raise (in case of error in fuel loading) and of water loss (in case of pool leakage) was also analysed.

The multiplication factor for the pools is evaluated for fresh fuel elements which is a conservative approach recommended by IAEA. Basically, the MCNP-4A Monte Carlo code [1] was used to model the pools. The CITATION [2] diffusion code was used at normal conditions to establish its applicability as a tool for time saving spent fuel storage calculations.

In section: ”Description of the spent fuel storage pools” geometry of Pool_1 and Pool_2 is described, in section: ”Calculation methods” both MCNP and CITATION model is explained, in section: ”Results and their discussion” the results are shown together with their discussion and conclusions. References are given at the end of the paper.

Description of the spent fuel storage pools

Description of Pool_1:

The spent storage for Etrr_1 reactor is a trapezoidal aluminium tank of 1.2 cm wall thickness [8]. The storage area is

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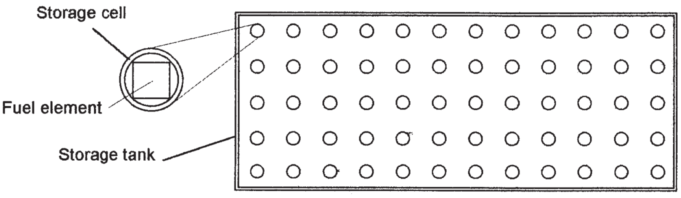

Fig. 1. Spent fuel storage pool for Etrr_1 reactor.

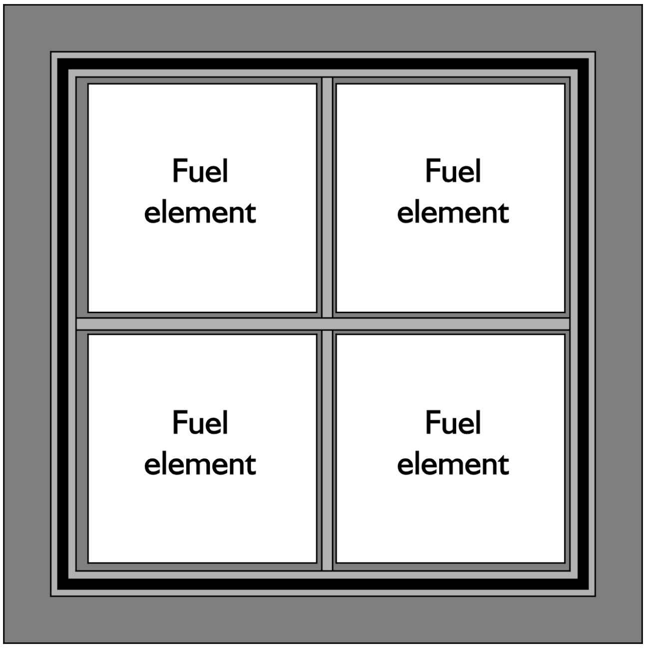

Fig. 2. Asymptotic storage cell for Etrr_2 reactor.

a rectangle with dimensions of 75×180 cm. The spent fuel elements are stored in storage cells. Each storage cell is a tube made of aluminium with 0.5 cm wall thickness and 11 cm outer diameter. The pool contains 60 storage cells placed in a square 5×12 array, forming a lattice of asymptotic storage cells with a pitch of 15 cm. The pool and the storage cell layout are shown in Fig. 1.

The Etrr_1 fuel element active height is 50 cm. Fuel element consists of 16 fuel rods, with the diameter of 0.7 cm. The fuel rod pitch is 1.75 cm, its aluminium clad thickness is 0.15 cm. The fuel meat density is 5.539 g/cm^3 with ^{235}U, ^{238}U, Mg and O_2 weight fractions equal to 7.553%, 68.774%, 12.225% and 11.448%, respectively.

Description of Pool_2

Pool_2 is an auxiliary pool located beside the reactor [9]. The pool is designed to store the spent fuel for the whole reactor lifetime, therefore its active diameter is ~4.5 m. The fuel elements are stored in 2 layers, separated with 30 cm of water. The fuel is stored in the storage cells – square metal boxes with outer dimension of 18 cm. The cells are placed in a square array, forming a lattice of asymptotic storage cells with a pitch of 21 cm. The pool contains approximately 250 storage cells. Each cell contains four (2×2) storage places for fuel elements. The wall of the cell consists of 3 layers: stainless steel, cadmium and stainless steel, each of thickness of 0.1 cm. The inner, cross-shaped frame is made of 0.1 cm thick stainless steel. The geometry of the storage cell is shown in Fig. 2. The Etrr_2 fuel element active height is 80 cm and transversal dimension is 8×8 cm. Each fuel element is formed of 19 plates. Each plate consists of fuel meat of thickness of 0.07 cm and aluminium clad of thickness of 0.04 cm. The distance between fuel plates is 0.27 cm. The material of fuel meat is U_3O_8 dispersed in aluminium matrix. The fuel meat density is 4.802 g/cm^3 with ^{235}U, ^{238}U, Al and O_2 weight fractions equal 12.375%, 50.044%, 25.9% and 11.681%, respectively.

Calculation methods

MCNP model:

For Etrr_1 both the asymptotic storage cell and entire storage pool were modelled using the MCNP 4A code. In the latter model, geometry of a single storage cell was exactly represented and then the repeated structure capability of the code was used to fill the pool with 60 storage cells. Free boundary was assumed at the outer pool surface.

In the calculation of the asymptotic cell, the storage cell was placed in the centre of a square water region with the outer dimension corresponding to the lattice pitch of the storage cells, i.e. 15 cm. Reflective boundary conditions were assumed in the calculations.

For Etrr_2 pool model, only asymptotic storage cell, cf. Fig. 2, was considered because of the size of the pool. In other words, it was assumed that the leakage from such a big structure can be neglected thus giving an overestimated evaluate of K_{eff}. The asymptotic storage cell contained the storage cell with four fuel elements in a square region of outer dimension of 21 cm filled with water, cf. Fig. 2. As above, the reflective boundary conditions were assumed in the calculations.

For both pools the calculations were performed using 250 neutron cycles with 1000 neutron histories each. The first 25 cycles were used to develop the spatial form of the fission source profile and the results for the next 225 cycles were accumulated for the calculations of the multiplication factor of the pool. A continuous cross section option was selected in MCNP cross section library.

Citation model

The calculation was performed in two steps:

1. **Asymptotic storage cell calculation, using the WIMS code** [5]. This step was done to calculate the macroscopic cross sections for two zones of the pool: fuel element and structure material. The cross sections determined at this step were used in the second step. The cell calculations were done with 69 energy groups and the results were condensed to five groups with the boundaries at: 10 MeV, 0.821 MeV, 5.53 keV, 0.625 eV, 0.08 eV and 0.0 eV (energy groups No. 5, 15, 45, 57 and 69 in the WIMS library). This step was performed both for Pool_1 and Pool_2.

2. **Global pool calculation.** This step was performed using the CITATION code to determine the effective multiplication factor of the pool. A three dimensional model for Pool_1 and Pool_2 was created and the condensed macroscopic cross sections, calculated at the previous step, were used to perform the global criticality calculations.

Results and their discussion

For normal conditions the multiplication factors were calculated at 20°C. In addition K_{eff} was determined at several pool temperatures, and dry conditions (total loss of water from the pool). Besides, the key parameters that affect the multiplication factor were varied. For Pool_1 the lattice pitch was diminished from 15 to 11 cm, which is the minimum value when the storage cells coincide. For Pool_2 mass of fissile material in the fuel element was increased, and the effect of cadmium layer on the multiplication factor of was evaluated. The calculations assume storing fresh fuel in the pools, which is a conservative approach [3, 4, 6, 7] that introduces a safety factor in the results.

Table 1. K_{eff} for Pool_1.

Code	Region considered	K_{eff}	Standard deviation
MCNP	Whole pool	0.521480	0.00136
MCNP	Asymptotic cell	0.555080	0.00130
CITATION	Whole pool	0.597068	–

Table 3. Variation of K_{eff} with mass of ^{235}U for Pool_1.

^{235}U mass(g) in fuel element	K_{eff}	Standard deviation
96	0.51575	0.00170
128	0.52148	0.00136
240	0.64745	0.00249
480	0.71287	0.00224
600	0.73254	0.00220

Results for Etrr_1 spent fuel storage

Table 1 shows the multiplication factor for Pool_1 at normal conditions. The results obtained with CITATION code are compared with those from MCNP code. It can be seen that the error in K_{eff} introduced by diffusion theory and the procedure of asymptotic cell homogenisation are several percent. However, the results given by CITATION are higher, so that the code can be used as a conservative tool for quick, qualitative assessment of the consequences of possible fuel element transfers in the pool.

Table 2 shows the multiplication factor for the pool as calculated with MCNP code at different pool temperatures. The results show an insignificant change for K_{eff} with temperature so that the pool remains subcritical with increasing temperature. For accident of total water loss, i.e. water replaced by air in MCNP calculations $K_{eff} = 0.02418$.

Table 3 shows the multiplication factor for the pool as a function of the element ^{235}U mass. The nominal fresh fuel element contains 128 g of ^{235}U. The multiplication factor with ^{235}U mass below 128 g corresponds to the value expected for the spent fuel, while K_{eff} for the mass > 128 shows the capability of the pool to store other possible fuel elements which contain larger mass of ^{235}U. The highest K_{eff} is well below 1.0, so that safety of the pool is confirmed.

Table 4 shows the multiplication factor of the pool as a function of the distance between the storage cells. The subcriticality of the pool, even for the tightest lattice pitch is confirmed.

Table 2. Variation of K_{eff} with temperature for Pool_1.

Temperature (°C)	Water density (g/ccm)	K_{eff}	Standard deviation
20	0.998	0.52148	0.00136
40	0.992	0.52253	0.00127
60	0.983	0.52618	0.00121
80	0.972	0.52324	0.00127
100	0.959	0.52004	0.00137

Table 4. Variation of multiplication factor of Pool_1 with lattice pitch.

Pitch (cm)	K_{eff}	Standard deviation
15	0.52148	0.00136
14	0.63479	0.00140
13	0.70258	0.00135
12	0.78123	0.00132
11	0.86238	0.00136

Table 5. K_{eff} for Etrr_2 asymptotic cell.

Code	K_{eff}
MCNP4A	0.77385
MONK 6.3	0.756
CITATION	0.7747

Table 7. Dependence of K_{eff} for Pool_2 on ^{235}U mass per fuel element.

^{235}U mass in fuel element	K_{eff} with cadmium	K_{eff} without cadmium
133.0	0.47641	1.02487
285.0	0.69067	1.22333
404.8	0.77385	1.29437
500.0	0.85120	1.33740

Results for Etrr_2 spent fuel storage

Table 5 shows the multiplication factor at normal conditions for Etrr_2 obtained using CITATION and MCNP codes. In addition, the results taken from reference [9], obtained using the MONK code, are shown for corroboration. Unexpectedly good agreement is observed between MCNP and CITATION results, which confirms the validity of the latter for qualitative assessment of the consequences of possible fuel element transfers in the pool. The agreement between CITATION and MONK is worse but both K_{eff} values are strongly subcritical, which confirms the safety of the pool.

Table 6 shows the variation of multiplication factor for Pool_2 with temperature, the results show an insignificant change with temperature.

Table 7 shows the variation of the multiplication factor for the pool with mass of ^{235}U per fuel element, which corresponds to a situation of erroneous loading of the fuel and at the same time shows the pool capacity for storing fuel with a higher enrichment. The calculations were repeated with and without cadmium in the walls of the storage cell. The results show that with cadmium layer the pool is subcritical even if the ^{235}U mass increased to 600 g per fuel element. Without cadmium the pool is supercritical. The supercriticality of the pool with Cd replaced with stainless steel is greater than in reality due, in part, to the conservative assumption in the calculations that all surfaces of the storage cell of Pool_2 are reflected. For accidental total water loss i.e. water replaced by air in MCNP calculations, $K_{eff} = 0.03146$.

Table 6. Variation of K_{eff} for Pool_2 with temperature.

Temperature (°C)	Water density (g/ccm)	K_{eff}	Standard deviation
20	0.998	0.77385	0.0017
40	0.992	0.77178	0.0018
60	0.983	0.77011	0.0016
80	0.972	0.76738	0.0016
100	0.959	0.76521	0.0014

Conclusions

– The safety of Pool_1 and Pool_2 has been confirmed, as their multiplication factors are less than one for all operating conditions.

– In the Pool_1 K_{eff} is smaller than unity even for the tightest possible lattice pitch, i.e. 11 cm, while for the Pool_2 cadmium layer must be used to ensure K_{eff} smaller than unity.

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