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Criticality Safety Assessment of a TRIGA Reactor Spent Fuel Pool under Accident Conditions

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Abstract

An overview paper on the criticality safety analysis of a pool type storage for a TRIGA spent fuel at the "Jožef Stefan" Institute in Ljubljana, Slovenia, is presented. It was shown in [1] that subcriticality is not guaranteed for some postulated accidents (an earthquake with subsequent fuel rack disintegration resulting in contact fuel pitch). To mitigate this deficiency, a study was made about replacing a certain number of fuel elements in the rack with absorber rods [2] in order to lower the probability for supercriticality to acceptable level.

1. Introduction

It was shown in [1] for spent fuel storage pool at 250kW TRIGA reactor operated by "Jožef Stefan" Institute in Ljubljana, Slovenia, that for some postulated accident conditions (an earthquake followed by total fuel rack disintegration where fuel elements pile together to contact and water remains in the pool) subcriticality cannot be guaranteed. This deficiency was mitigated by the replacement of certain number of fuel elements by the absorber rods [2], thus lowering the probability for supercriticality to acceptable level. Since the same pool would be used for emergency core unloads also, the calculation with the most reactive, fresh 12 wt% standard TRIGA fuel was performed to cover the possibility for such unload to occur in the very beginning of the core life.

The criticality analysis was performed by calculating the multiplication factor (denoted as k_{eff} further in the text) for the spent fuel pool for the pitch being decreased from the design pitch of 8cm down to contact in a square arrangement of the fuel and the absorber rods, and additionally, for the most compact, hexagonal contact arrangement.

Besides, a short study of different absorber rod designs and different materials was done. Due to its availability, cadmium was chosen as an absorbing material.

After the determination of the critical number of fuel elements for both modes of compaction (the square and the hexagonal contact pitch arrangements) was done, the number of uniformly mixed absorber rods in the lattice needed to sustain the subcriticality of the storage is studied (again for both lattice loading modes), assuming that the fuel elements and the absorber rods keep their relative positions.

It was further assured that random mixing of the absorber rods and the fuel elements occurs during the lattice compaction. Therefore, the possibility for supercriticality cannot be excluded. A probabilistic study was made in order to sample the probability density functions for random lattice loadings of the absorber rods. From the obtained probability density functions, the probability for the supercriticality immediately follows.

2. Description of the pool and the absorber rods

The pool, excavated in the basement of the reactor hall, is 2.6×2.6m wide and 3.6m deep. It is filled with pure demineralised water. The walls are made of reinforced concrete clad with stainless steel. The aluminium fuel rack is attached to the bottom of the pool, consisting of top and bottom support plates connected by vertical props at the sides. Top support plate has 21×10 holes for inserting fuel elements. Pitch is 8cm and the hole diameter is 4cm. Holes are arranged in a square array. The rack is divided in three segments of 7×10 positions by aluminium-clad cadmium plates (see Fig. 1).

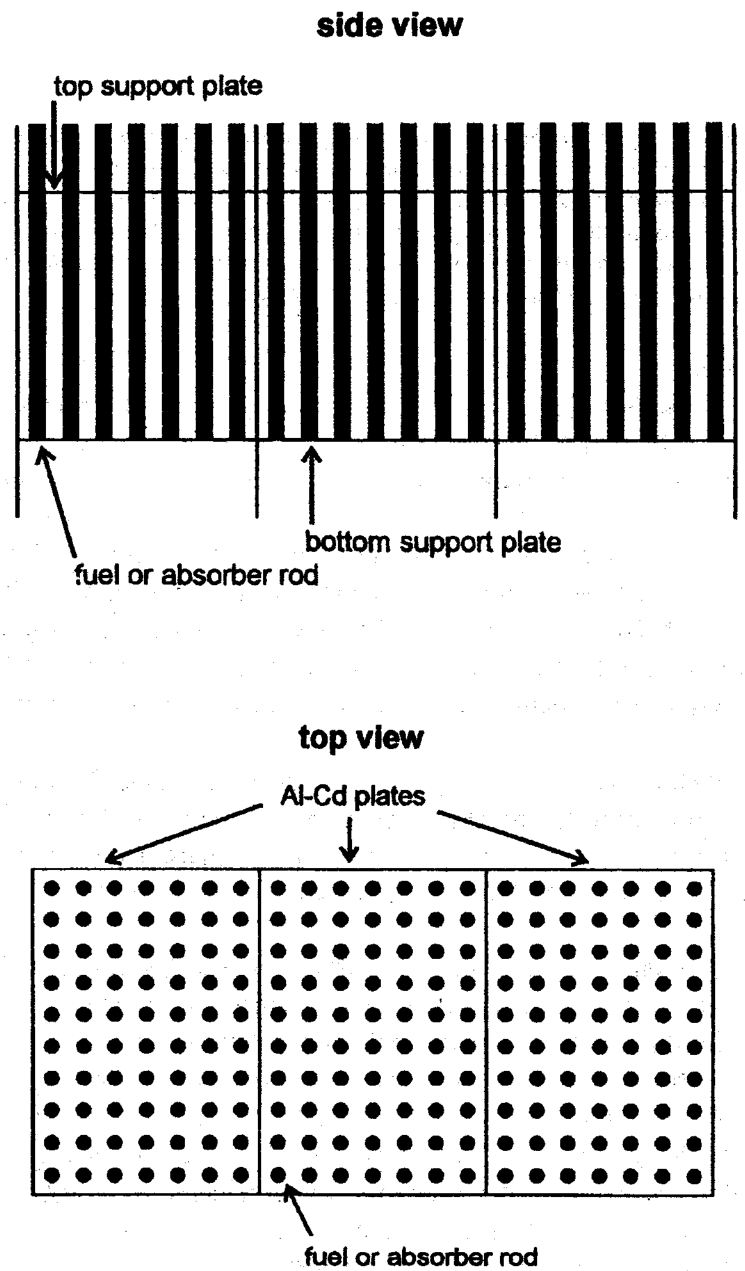

Fig. 1: Side and top views of the spent fuel pool rack at TRIGA Ljubljana [2]

During the postulated accident, when random mixing of the fuel elements and absorber rods and their compaction to contact pitch can be expected, equal probability must be assured that either fuel elements or absorber rods would occupy one of the available lattice positions. This can be achieved if mechanical properties, i.e. the shape and the weight of both element types, are the same.

A short study for absorber rods, made of cadmium for the Cd layer thickness between 0.0001mm and 15mm is presented (Fig. 2). It can be seen that the influence of the thickness of absorbing layer on the multiplication factor plays little role for values greater than 1mm [3]. Due to its availability, cadmium was chosen as an absorbing material in further calculations. The final shape of the absorber rod was modelled with top and bottom plugs made of stainless steel and 6.2mm thick cadmium plate, rolled in the form of hollow cylinder, to match exactly the total weight of standard fuel element.

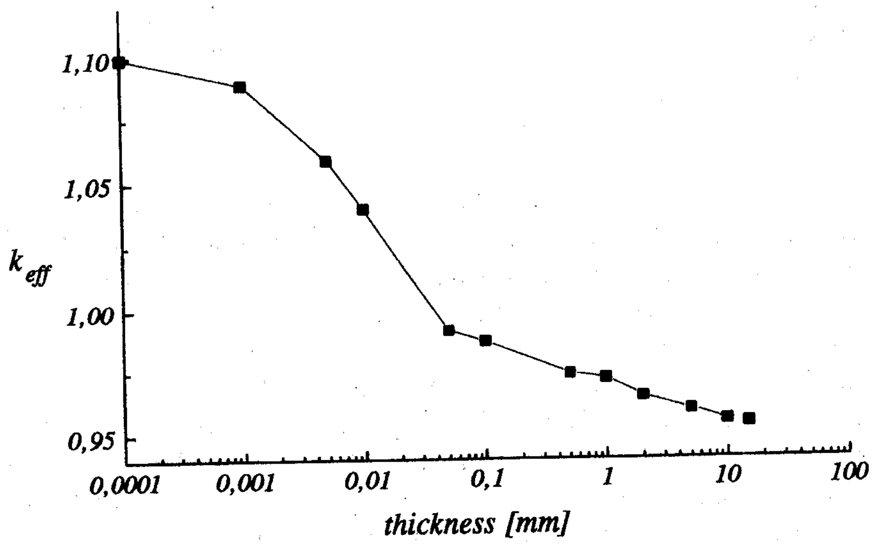

Fig. 2: k_{eff} for the pool with cadmium rods versus the thickness of cadmium layer

3. Calculational method

Monte Carlo computer code MCNP4B [4] was used. A continuous neutron cross section library, evaluated from ENDF/B-VI data [5,6] was applied. The scattering functions for graphite, hydrogen in water molecule and hydrogen in zirconium were taken from the ENDF/B-IV library. Detailed three-dimensional geometry was used. Both the fuel elements and the absorber rods were exactly modelled, as well as the pool, so that axial and radial leakage is described correctly.

4. Results

4.1 Critical number of 12 wt% fuel elements in contact

The first task of our analysis was to determine the critical number of fresh standard 12 wt% fuel elements for square and hexagonal contact lattice pitch. It was assumed that, during the rack disintegration, all fuel elements pile together to square contact in two possible modes, that is along the short side or along the long side of the rack. Water is assumed to remain in the pool. We started our calculation with a certain subcritical number of fuel elements and then sequentially added fuel elements for both lattice modes until criticality was achieved. Other available lattice locations contained only water. The same calculation was performed for hexagonal contact lattice pitch, where it was supposed, that the fuel elements and the absorber rods from each of three segments form a triangular pile on the bottom of the pool.

The second task of the analysis followed the same reasoning as before, differing only in that previously water filled lattice positions were now replaced with above described cadmium absorber rods.

The results showing the critical number of fuel elements for described situations are given in the Table I.

Table I: Critical number of fuel elements

	fuel elements	fuel el. + Cd rods
short side loading	35	39 + 31
long side loading	46	48 + 22
hexagonal loading	52	58 + 12

The given results are quite understandable: the first mode of loading has the denser pile configuration than the second one. It is closer to the spherical (or cylindrical) reactor model and the second one to a slab reactor model. The highest critical number of fuel elements for hexagonal loading is due to a worse moderation (lower moderator / fuel ratio).

The third column of the Table I, representing the critical number of fuel elements, where previously water flooded lattice positions are now filled with cadmium absorber rods, shows that additional cadmium absorbers, when piled along one side of the fuel rack and fuel elements along the opposite side, cannot essentially lower the k_{eff} during the rack disintegration and lattice compaction. However, as it will be shown, the probability for such an event to occur appears to be negligibly small.

4.2 Criticality for uniformly loaded absorber rods during pitch decrease

To show that uniformly mixed absorbers among the fuel assure subcriticality under postulated accident conditions, a certain number of absorber rods (8, 10, 12, 15, 17 and 20) was mixed among the squarely arranged fresh fuel elements in a more or less regular manner. k_{eff} was calculated for different pitches from the design pitch of 8cm down to square contact pitch for every chosen number of absorber rods (Fig.3). The similar calculation was done for the hexagonal contact pitch, where 2, 4, 6, 8, 10 and 12 absorber rods were inserted into the lattice (Fig. 4).

Results show that, for square arrangement, even only 8 uniformly positioned absorber rods among 62 fuel elements assure subcriticality for all pitches down to contact, and only 4 uniformly positioned absorber rods among 66 fuel elements assure subcriticality for contact pitch with hexagonal packing. Result for fuel elements in all 70 positions (no absorber rods) is added to confirm our concern about supercriticality if no additional absorber rods are inserted into the lattice.

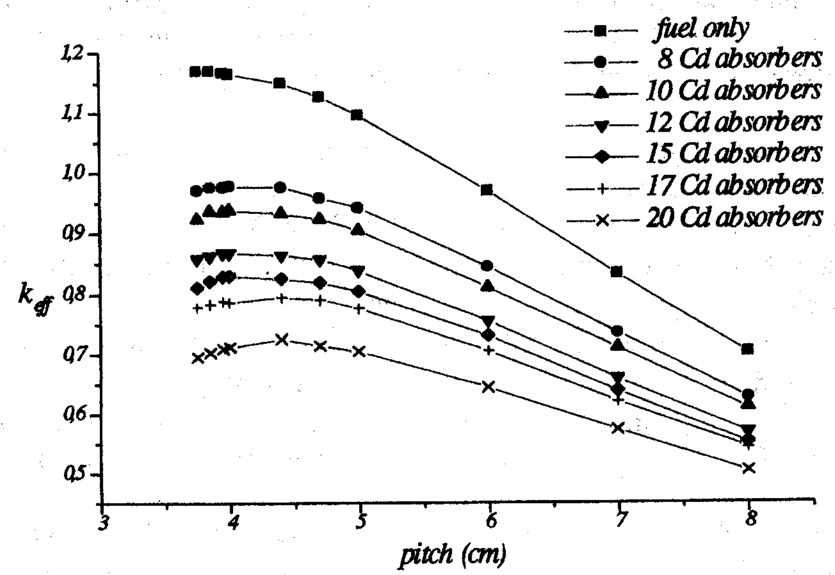

Fig. 3: k_{eff} for various numbers of uniformly loaded Cd rods for square arrangement versus the lattice pitch.

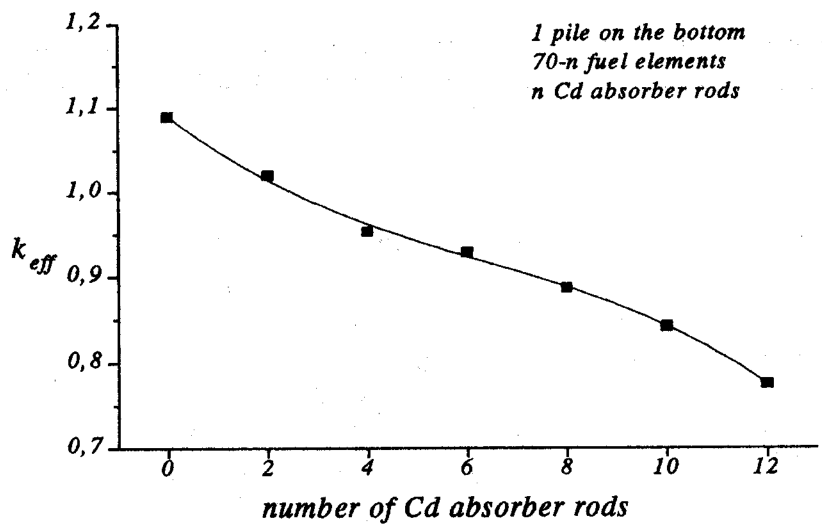

Fig. 4. k_{eff} versus the number of Cd absorber rods for the hexagonal contact pitch arrangement

4.3. Supercriticality probability estimation

In the case of random mixing of fuel elements and absorber rods, a non-zero probability for supercriticality can be expected. There are N possible ways to load n indistinguishable absorber rods and 70 - n indistinguishable fuel elements into this lattice. N is given by

$$N = \frac{70!}{n!(70-n)!} \tag{1}$$

For example, if n = 20, N is approximately $1.62 \cdot 10^{17}$. So, the probability for each possible loading, like, for example, all fuel to one side and absorber rods to another side, would be negligibly low, i.e. 10^{-17}. This occurrence is highly unprobable, but the possibility for some other supercritical loadings can be expected.

To determine the probability for supercriticality for the square and hexagonal arrangement, two similar calculational schemes were used:

- a program was written for preparing 500 different MCNP inputs, describing 70 - n fuel elements and n absorber rods randomly distributed in a square and hexagonal contact pitch arrangement for every chosen n;
- after the execution of the MCNP runs, the MCNP output files were checked and k_{eff} and its standard deviation σ were retrieved and incorporated into the probability density file (simply, unity was added to a vector between $k_{eff} - \sigma$ and $k_{eff} + \sigma$ with resolution of 0.0001 in order to cumulatively build the probability density function);

This calculational scheme was done for all selected numbers of absorber elements n (8, 10, 12, 15, 17 and 20 for square arrangement and 4, 6, 8, 10 and 12 for hexagonal arrangement). The accumulated probability density functions $\partial p_n/\partial k_{eff}$ were then normalised in order to define the probability for supercriticality $p_n(k_{eff} \geq 1)$:

$$p_n(k_{eff} \geq 1) = \int_{k_{eff} \geq 1} \frac{\partial p_n}{\partial k_{eff}} dk_{eff} \qquad (2)$$

The samples of cumulatively built probability density functions $\partial p_n(k_{eff})/\partial k_{eff}$ for some numbers of absorber elements for hexagonal arrangement are presented in Fig. 5.

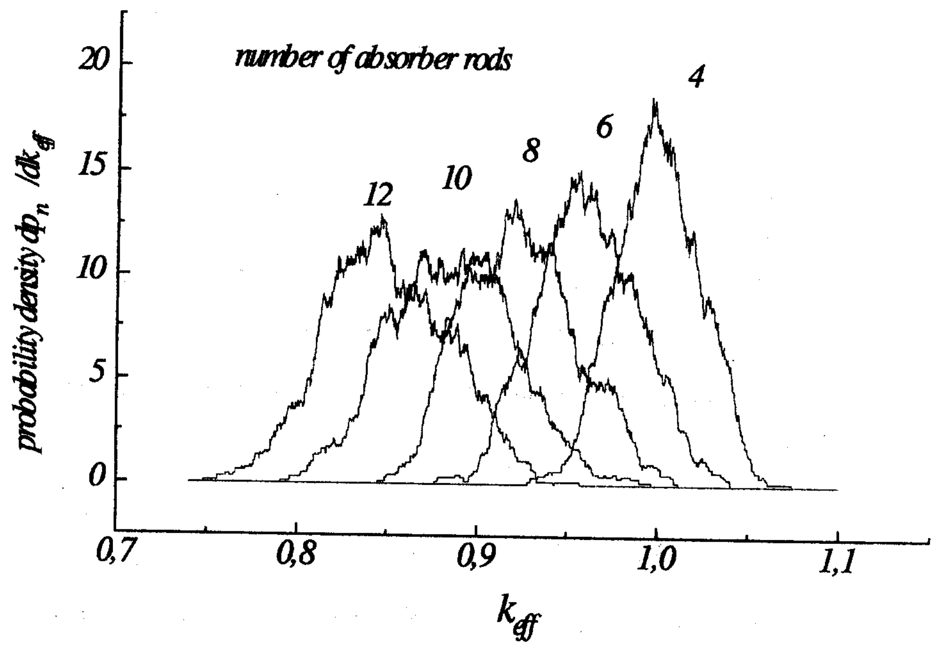

Fig. 5. Probability density functions $\partial p_n(k_{eff})/\partial k_{eff}$ for selected numbers of randomly loaded absorber rods (hexagonal packing)

From the obtained probability density functions the probabilities for supercriticality directly follow from Eq. (2). They are given in the third column of Table II. Although 500 MCNP runs were done for each number of absorber elements, the curves of the "experimental" probability density data still show scatter. To avoid this, the gaussian and exponential least squares fits were applied to the right hand side tail of the "experimental" probability density functions. Although that gaussian provides better fit, both gaussian and exponential supercriticality probability estimations are included in Table II for illustrative purposes.

Table II: Probability for supercriticality ($k_{eff} \geq 1$) for various number of randomly loaded absorber rods for hexagonal and square contact pitch (3.75cm)

	Number of randomly loaded Cd absorbers n	Probability for $k_{eff} \geq 1$		
		"experimental" data	gaussian tail	exponential tail
hexagonal arrangement	4	0,48497	0,49050	0,52001
	6	0,09127	0,09683	0,09732
	8	0,00534	0,01224	0,00568
	10	0	0,00008	0,00058
	12	0	0,00002	$8{,}7 \cdot 10^{-6}$
square arrangement	8	0,75	/	/
	10	0,35	/	/
	12	0,062	0,069	0,12
	15	0,0026	0,0036	0,033
	17	0	0,0011	0,015
	20	0	$1{,}3 \cdot 10^{-6}$	0,0045

5. Conclusions

As it was shown in [1] and confirmed in [2] subcriticality is not guaranteed in severe accident conditions for the new spent fuel storage pool at TRIGA reactor in Ljubljana, Slovenia, if rack disintegration with lattice compaction to square contact pitch would occur and if, at that time, only fresh 12 wt% standard TRIGA fuel elements alone would be stored in the pool. Later on, a study about replacing some of fuel elements in the rack by cadmium absorber rods and a proper criticality safety analysis was done [2]. At last these results were completed with the supplemental study for most compact, i.e. hexagonal arrangement of the fuel elements and absorber rods.

It was supposed that in a case of an earthquake the fuel rack disintegrates and fuel elements and absorber rods pile together in two ways: making square contact pitch piles or compacting hexagonaly by making triangular piles at the bottom of the pool. Multiplication factor k_{eff} was calculated for different numbers of absorber rods for both ways in two modes: first, for uniformly distributed absorbers among the fuel elements in the pile, and second, for randomly distributed absorbers among the fuel elements. Monte Carlo computer code MCNP4B with ENDF/B-VI cross section library was used to perform the analysis.

It is obvious that hexagonal distribution is undermoderated, so, in order to assure the maximum possible safety of the fuel storage, the conclusions from [2] should be considered:

- Without any absorbers only 34 fuel elements would be maximum number to be stored in one fuel rack compartment, since any larger number would probably lead to criticality under severe earthquake conditions.
- For absorber rods uniformly mixed with fuel in the case of postulated accident, only 8 absorber rods would assure subcriticality.
- Since random mixing of fuel elements and absorber rods leading to subsequent supercriticality during lattice disintegration can be expected, an extensive Monte Carlo calculation was done to sample the probability for supercritical configurations that may occur, if there are more than 34 fresh standard 12 wt% TRIGA fuel elements stored in one fuel rack compartment.
- When there are 15 - 20 absorber rods used in a single rack compartment, the probability for supercriticality falls reasonably low (10^{-6} - 10^{-3} for postulated accident, resulting in rack disintegration and unfavorable mode of fuel compaction). This enables the storage of up to approximately 20 fresh standard 12wt% TRIGA fuel elements more in each fuel rack compartment.

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