CRITICALITY OF A SPENT FUEL POOL FILLED WITH BURNED FLIP FUEL

Marjan Logar
University of Maribor
Faculty of Electrical Engineering and Computer Science
Smetanova 17, SI-2000 Maribor, Slovenia
marjan.logar@uni-mb.si

Robert Jeraj, Bogdan Glumac
“Jožef Stefan” Institute
Reactor Physics Division
Jamova 39, SI-1000 Ljubljana, Slovenia

ABSTRACT

It has been shown that supercriticality might occur for some postulated accidents for the TRIGA spent fuel pool at “Jožef Stefan” Institute in Ljubljana, Slovenia. Until recently, the analyses were mainly done with all types of fresh fuel in the storage. As the effect of burned standard fuel was already done, similar analysis is presented here for burned FLIP fuel in the storage pool. Besides the dependence of criticality on FLIP fuel burnup, the influence of pitch among the elements and the number of uniformly mixed absorber rods for a square arrangement are studied also.

The Monte Carlo computer code MCNP4B with ENDF-B/VI library and detailed three dimensional geometry was used. WIMS-D code was used to model the isotopic composition of fresh and 5, 10, 20 and 30 % burned fuel immediately after the removal from the core and for 2 and 4 years cooling time.

The results show that out of the three studied effects (pitch from contact (3.75 cm) up to rack design pitch (8 cm), number of absorbers from 0 to 8 and burnup up to 30 %) the pitch has the greatest influence on the multiplication factor k_{eff}. In the interval in which the pitch was changed, k_{eff} decreased for around 0.3. The number of absorber rods affects the multiplication factor much less. This effect is bigger for more compact arrangements, e.g. for contact of fuel elements with 8 absorber rods among them, k_{eff} decreases for more than 0.1 almost regardlessly of the burnup. For 8 cm pitch the same effect is smaller for some 30 %. The effect of burnup is the smallest one. In all cases the k_{eff} changes for 0.02 to 0.04, but due to the increased reactivity with burnup, k_{eff} increase for compact arrangement and k_{eff} decrease for 8 cm pitch could be seen. Cooling of fuel has just a minor effect on the criticality of spent fuel pool and can be neglected in spent fuel pool design.

1 INTRODUCTION

So far the burnup credit criticality safety analyses for spent fuel facilities have been done for power reactor fuel only, because of their close to maximum spent fuel pool storage capacities [1, 2]. To increase the storage capacity, two ways are usually studied and
implemented: changes in the pool design (reracking) and the implementation of analyses considering reduced conservatism (burnup credit) [3, 4]. For research reactor spent fuel pools, where the problems of nearly full storage capacities are not so drastic, some such analyses have been published [5]. However, due to similar reason as for power reactor spent fuel storage pools, considering the burnup of the fuel elements in criticality analyses of the pools, enables proposals that could be beneficial for determining acceptable risk and lowering the cost while keeping the requested safety margins.

It was shown in [6] that for some postulated accident conditions (like an earthquake followed by fuel rack disintegration where fuel elements approach each other to contact and water remains in the pool) subcriticality cannot be guaranteed for spent fuel storage pool at 250 kW TRIGA Mark II reactor operated by “Jožef Stefan” Institute in Ljubljana, Slovenia. This deficiency was mitigated by the replacement of some fuel elements by absorber rods, thus lowering the probability for supercriticality to an acceptable level. Different cases of pitch decrease, for square and hexagonal arrangements, different absorber materials and their shape were analyzed [7, 8]. In the previous studies, fresh fuel elements were considered in the pool. The burnup influence has not been studied systematically. For real cases, where fuel elements are burned, a study of realistically burned elements instead of fresh may reduce safety margins and the cost of the pool.

The present work analyzes similarly as in [5] the spent fuel pool for realistic burned FLIP fuel elements. They were modelled for certain burnup levels including 2 and 4 years cooling time. Beside the burnup, the role of the pitch decrease (simulating the fuel compaction in a case of an accident) and the number of absorber rods were investigated.

2 MODEL OF THE POOL

The geometry model for our calculation was based on our pool that is located in the basement of the reactor hall, and is 2.6×2.6m wide and 3.6m deep. It is filled with pure demineralized 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. Holes are arranged in a square array with 8 cm pitch. The rack is divided in three compartments of 7×10 positions by aluminium-clad cadmium plates.

Due to its availability, cadmium was chosen as an absorbing material. The shape of the absorber rod was modelled with top and bottom plugs made of stainless steel and 1 mm thick cadmium plate, rolled in the form of a hollow cylinder, to fit exactly into the fuel-element-like cladding.

In the model, the pitch was varied between 3.75 and 8 cm, simulating this way the compaction of fuel elements from the rack design pitch to the contact pitch. In this way we wanted to describe the possibility of fuel compaction on the bottom of the pool that could happen in the case of an earthquake, followed by disintegration of the rack.

3 ISOTOPIC COMPOSITION OF BURNED FLIP FUEL ELEMENTS

During operation of a reactor, the isotopic composition of the fuel elements changes because of fuel burnup. Magnitude of these changes and their time dependence have an important impact on the reactor working regime. Approximately 200 different fission products are generated, some directly via fission, some indirectly via radioactive decay. Many of them have high neutron absorption cross sections. If there is significant amount of them, their influence on reactivity and on multiplication factor could be considerable.
Experimental methods for determination of burnup are complicated. More practical and therefore more often used are theoretical methods. Because exact calculation of the burned fuel isotopic composition is difficult, some approximations have to be introduced.

The large number of fissile products could be handled in two ways. Only those fission products having high cross sections for neutron capture should be dealt with explicitly, while those with small cross sections could be lumped together into one or more groups and assigned an average cross section. Nuclides $^{135}\text{Xe}$ and $^{149}\text{Sm}$, having very high total cross sections for thermal neutrons ($3 \times 10^6$ in $4 \times 10^5$ barn), are always treated individually. Criteria for the nuclides to be treated explicitly are described in [9].

Stable and long-lived nuclides are accumulated in burned fuel, so their concentration increases with burnup. The elements are cooled for at least a year or more after the removal from the core, so the nuclides with short half lives practically do not exist anymore when fuel is stored in the storage pool. Their relative contribution to the reactor criticality ($\Delta k_{\text{eff}}/k_{\text{eff}}$) at 20 % burnup is less than $50 \times 10^{-5}$ [10].

4 MATERIALS AND METHODS

The MCNP4B Monte Carlo computer code [11] and a continuous neutron cross section library, mainly evaluated from the ENDF/B-VI data [12, 13], were used in our studies. For most fission products the data from the ENDF/B-VI library were used. Kr, Mo, Ru, Rh, Pd, Cd, Nd, Pm, Sm and Eu data were taken from the ENDF/B-V library, because they were not reevaluated in the ENDF/B-VI. The thermal scattering data for graphite, hydrogen in water molecule and hydrogen in zirconium were taken from the ENDF/B-IV library. Detailed three dimensional geometry was modelled. Both the fuel elements and the absorber rods were modelled accurately, as well as the pool, so that the axial and radial leakage was automatically accounted for. In every calculation 2000 neutrons were simulated per each of 2000 generations, so the standard deviation in the calculated $k_{\text{eff}}$ was approximately $30 \times 10^{-5}$.

In our study, the criticality analysis was performed by calculating the effective multiplication factor $k_{\text{eff}}$ for the spent fuel pool, filled with fresh FLIP fuel and the fuel with 5, 10, 20 and 30 % burnup. The isotopic composition for burned fuel was determined using the WIMS-D code [14]. The reason for doing so is that MCNP4B code does not have possibility to determine the burned fuel composition. However, it was shown [15] that it is possible to reliably treat examples with burned fuel by combining the WIMS-D code with Monte Carlo calculations. Most of the isotopes calculated with WIMS can be accounted for in MCNP with the exception of the pseudo fission product and some other rare isotopes. However, as shown in [10], the contribution of the pseudo fission product as well as the other rare isotopes on the reactivity ($=10^{-4}$) can be neglected because it was below the statistical uncertainty of our simulations. The isotopic composition was calculated from a specific burning power of 10 kW and appropriate time of burning. The change of isotopic concentration with cooling time of 2 and 4 years was calculated, too. But it is almost negligible for majority of fission products, except for those nuclides with short decay time.

Besides the change of isotopic composition, the influence of pitch decrease from the rack design pitch (8 cm) down to contact (3.75 cm) in a square arrangement of the fuel and the absorber rods, and the influence of the number of absorber rods were studied for fuel only and 4, 6 and 8 uniformly mixed absorber rods.
5 RESULTS

Results of the calculated multiplication factors $k_{\text{eff}}$ for spent fuel pool are presented graphically in Figures 1 to 3. On the z axis the $k_{\text{eff}}$ values are indicated by the color palette (shown at the edge of every figure) as functions of the fuel element burnup and pitch among the fuel elements for different number of absorber rods. Figure 1 shows $k_{\text{eff}}$ for fuel only, without absorber rods, and the next two figures for 4 and 8 absorber rods. The values for $k_{\text{eff}} = 1$ and $k_{\text{eff}} = 0.8$ are additionally marked with dotted lines.

The pool filled with fresh fuel only (no absorber rods) is critical up to $\sim 6.3$ cm pitch and with 30 % burnup reaches subcriticality for pitches larger than 6.2 cm For pool with 4 absorbers in each rack compartment (Figure 2) it can be seen, that the pool being loaded with fresh fuel, stays critical approximately up to the 4.9 cm pitch and that with 30 % burnup level gets critical for pitch less than 5 cm. Pool with 8 absorbers remains subcritical for all pitches and burnups (Figure 3). The $k_{\text{eff}} = 0.8$ value is met only for pitch less than $\sim 7$ cm.

Few examples of multiplication factor are shown in the Figures 4 to 6 for some chosen calculations in dependence of only one variable (burnup, pitch, number of absorbers), the others are presented as parameter. These are some chosen side views through the results presented in Figures 1 to 3.

The extreme changes in multiplication factor $k_{\text{eff}}$ of the pool, when pitch is increased from contact of the elements up to 8 cm, further, when there are no absorbers and when there are 8 of them in each rack compartment, and finally, when burnup of the fuel increases from 0 to 30 %, are brought together in Table 1.

We can see that the pitch has the greatest influence on the $k_{\text{eff}}$. In the investigated interval of the pitch, if there are no absorbers $k_{\text{eff}}$ decreases for more than 0.3 if only fresh FLIP fuel is in the pool or its burnup reaches 30 %; if there are 8 absorbers uniformly arranged among the fuel elements $k_{\text{eff}}$ decreases for less than 0.3.

The number of absorbers affects the multiplication factor much less. This effect is bigger for more compact arrangements, where the multiplication factor $k_{\text{eff}}$ decreases for more than 0.1 at any burnup, while this effect decreases $k_{\text{eff}}$ for 0.08 at the pitch of 8 cm.

The influence of burnup is the smallest; the only exception in previous trend is, that because of reactivity increase, the multiplication factor $k_{\text{eff}}$ increases slightly for compact arrangements of the fuel.

The critical burnup for the pool depends mainly on the number of absorber rods. In fact the pool with FLIP fuel inside can become supercritical for every burnup, when there are 0, 4 or 6 absorbers. Only for 8 absorbers the pool reaches subcriticality for all burnups and pitches.

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1 Technical specification recommended by the TRIGA reactors designer General Atomic Comp., demands such a geometrical arrangement of the fuel in the storage, that the multiplication factor would be less than 0.8 for all conditions of moderation.
Figure 1: $k_{eff}$ versus burnup and pitch for the pool with no absorbers

Figure 2: $k_{eff}$ versus burnup and pitch for the pool with 4 absorbers

Figure 3: $k_{eff}$ versus burnup and pitch for the pool with 8 absorbers
Figure 4: $k_{\text{eff}}$ of the pool versus burnup, 4 absorber arrangement, pitch as parameter

Figure 5: $k_{\text{eff}}$ of the pool versus pitch, 4 absorber arrangement, burnup as parameter

Figure 6: $k_{\text{eff}}$ of the pool versus the number of absorbers, 30 % burnup, pitch as parameter
Table 1: Results resume: the change of multiplication factor due to change of pitch, number of absorbers and burnup

<table>
<thead>
<tr>
<th>Pitch increase: 3.75 – 8 cm</th>
<th>Absorbers</th>
<th>Burnup</th>
<th>Δk_{eff}</th>
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<tr>
<td></td>
<td>0</td>
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</tr>
<tr>
<td></td>
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<td>-0.37</td>
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</tr>
<tr>
<td></td>
<td>8</td>
<td>0 %</td>
<td>-0.26</td>
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<tr>
<td></td>
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<table>
<thead>
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<th>Burnup</th>
<th>Δk_{eff}</th>
</tr>
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<td></td>
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<td>0 %</td>
<td>-0.12</td>
</tr>
<tr>
<td></td>
<td>30 %</td>
<td>-0.14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8 cm</td>
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</tr>
<tr>
<td></td>
<td>30 %</td>
<td>-0.08</td>
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<table>
<thead>
<tr>
<th>Burnup increase: 0 – 30 %</th>
<th>Pitch</th>
<th>Absorbers</th>
<th>Δk_{eff}</th>
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</tr>
<tr>
<td></td>
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<td>-0.03</td>
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6 CONCLUSIONS

Results of this study show that out of the three parameters investigated (pitch, burnup, number of absorbers), the pitch has the greatest influence on the spent fuel pool multiplication factor $k_{eff}$. The effect of adding absorbers is much smaller, and is bigger for more compact arrangements. The smallest is the effect of burnup: with pitch increase and by adding the absorber rods the $k_{eff}$ reduction even falls lower.

The critical burnup for the pool depends mostly on the number of absorbers. The pool can become supercritical for every burnup and less than 8 absorbers. For 8 absorbers the pool is subcritical for all burnups and pitches.

It may be concluded that burnup does not have strong influence on the criticality of the spent fuel pool, however, one should be aware that the results with fresh fuel may be for less than 0.1 too conservative in $k_{eff}$ for burnups up to 30 %.

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REFERENCES

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