ABSTRACT

Modern Monte-Carlo codes (e.g. MCNP) allow calculation of the power density distribution in 3-D geometry assuming detailed geometry without unit-cell homogenization. The power density distribution (and its maximum value - the peaking) can be calculated ‘point-wise’ with the resolution of approximately 1 mm. Results of the detailed power density distribution calculated by MCNP are presented for 250 kW TRIGA Mark II reactor, assuming various realistic and hypothetical core loading patterns with focus on the mixed cores. Combinations of 8.5 w/o, 12 w/o, 20 w/o and 30 w/o low enriched (20 %) fresh TRIGA fuel rods are systematically treated in the mixed cores. The power peaking factor value and position strongly depends on the core configuration. Power peakings are usually found in fuel rods with higher uranium content especially if they are inserted near the core centre. The results are conservative and can be applied in planning realistic mixed core loading patterns.

1 INTRODUCTION

Power distribution in the reactor core is normally calculated by the diffusion codes (e.g. TRIGLA V package) in 2-D approximation. Diffusion codes normally treat the fuel rods and surrounding water as homogeneous regions called unit cells. The detailed power density distribution is calculated in two steps. First step consists of power density calculation by the diffusion code in the entire reactor using homogenized unit cells. In the second step, the in-cell power density distribution is calculated by using a transport code (e.g. WIMS), taking into account detailed unit cell structure (fuel, cladding, water). The method is a variant of the flux synthesis method coupling the global and local reactor power distribution through preservation of fission rate in the unit cells. The decoupling of global and local power density calculation is the deficiency of this method. The method can not reproduce properly the effects of in-rod power gradients due to the heterogeneities in the core such as control rods, water gaps and differences in fuel enrichment or uranium concentration.

Modern Monte-Carlo codes (e.g. MCNP [1]) allow calculation of the power density distribution in 3-D geometry assuming detailed geometry without unit-cell homogenization. The power density distribution (and its maximum value - the peaking) can be calculated ‘point-wise’ with the resolution of approximately 1 mm.

Power peaking calculations are performed for several 250 kW TRIGA Mark II reactor core configurations: uniform and mixed core with standard and LEU fuel elements. Three types of fuel elements are considered: standard (8.5 w/o and 12 w/o) and LEU, all of them 20 % enriched. More results and a more detailed analysis can be found in reference [2].

2 CALCULATION METHOD AND MODEL

MCNP computer code [1] was used in the calculations. MCNP is a general-purpose, continuous-energy, generalized-geometry Monte Carlo transport code. The calculations reported in this paper were performed with version 5.1.40 of the code.
The reactor core model was very similar to the one used for benchmark evaluation of TRIGA mark II reactor [3], the main difference being in control rods and number of fuel elements. In order to observe power peakings arising only from differences in fuel composition and not from other disturbances (e.g. empty positions, control rods, irradiation channels, etc.) the core was made as homogeneous as possible by removing the control rods, empty positions and irradiation channels and replacing them with fuel elements. However central position was as in most TRIGA reactors filled with irradiation channel (i.e. aluminium tube filled with air), which prevents violation of design basis safety limits in the central fuel element. All fuel elements in the core were considered to be fresh.

The fission density and flux distribution were calculated in the following way. A mesh of 500 × 500 × 1 (length × width × height) cells, in which the neutron flux or fission density were calculated, was superimposed over the reactor core. Each cell measured 1 mm × 1 mm × 381 mm (height of the fuel in the fuel element), meaning that the flux and the fission density were averaged over the fuel element height. The calculations had to be performed in that way in order to obtain reasonable small statistical uncertainty, i.e. less than 1 %. Use of larger number of cells and calculation of axial power peaking factors was namely not possible due to following reasons: limited amount of computer memory that could be used by the code and large statistical uncertainty due to small number of neutrons in each cell.

3 POWER PEAKING FACTORS

Three power peaking factors are important for steady state operation [4]:
- hot rod peaking factor $f_{hr}$
- axial power peaking factor $f_z$ and
- total power peaking factor $f_{tot}$

They determine total power released by one fuel element as well as its peaking value which are used as parameters in thermal hydraulics analysis.

Hot rod power peaking factor is defined as the ratio between the maximum power released by one fuel element (rod), $P_{rod}$, and average power per element in the core, $P_{core}$.

$$f_{hr} = \frac{P_{rod\ max}}{P_{core}}$$ (1)

According to this definition

$$P_{core} = \frac{P}{N_{el}}$$, (2)

where $P$ is total reactor power (e.g. 250 kW) and $N_{el}$ is number of fuel elements in the core. Taking into account that all types of fuel elements have the same volume of fissionable material, the definition of $f_{hr}$ applies also to the ratio between the average power density $P_{rod}$ of the hot rod and core average power density $P_{core}$.

Since $f_z$ does not depend significantly on the fuel type or location in the core [5] and due to limited computational capabilities (as described in the previous section), $f_z$ values were not calculated. $f_z = 1.25$ is typical for Mark II TRIGAs with hard axial distributions [5].

Total peaking factor, $f_{tot}$, is defined as the ratio between the maximum power density in the core, $P_{max}$ and the average power density in the core, $P_{core}$.
\[ f_{\text{tot}} = \frac{p_{\text{max}}}{p_{\text{core}}} \]  

(3)

\[ f_{\text{tot}} \] can be split into two sub-factors, \( f_z \) and \( f_r \), axial and radial power peaking factor, such that

\[ f_{\text{tot}} = f_z \cdot f_r \]  

(4)

In our calculations, to reduce statistical error, fission density was averaged over the fuel element height. According to (3) and (4), the results correspond to the radial power density peaking factor \( f_r \). If one is interested in actual point wise maximal power density, \( p_{\text{max}} \) (in W/cm\(^3\)) in the core it is obtained from the calculated \( f_r \) using relation

\[ p_{\text{max}} = f_z \cdot f_r \cdot p_{\text{core}} \approx 1.25 \cdot f_r \cdot p_{\text{core}} \]  

(5)

The latter is especially important at pulsing where the temperature radial distribution is approximately proportional to the power density distribution as the pulse is so short (10 - 50 ms) that heat is practically not transferred from the point where it is released.

Calculated fission density radial distribution with the resolution of 1 mm × 1 mm is presented in Figure 5 for a mixed core (6 LEU in C-ring and standard 8.5% fuel). It can be observed that the power peaking is at the outer radius of LEU rod near the inter-fuel water gap. In-rod power density gradients due to the heterogeneities in the core such as water gaps and differences in uranium concentration can be clearly seen. Local fission density peakings at the edges of the LEUs in the B ring are also noticeable.

4 RESULTS

First \( f_{hr} \) and \( f_r \) were calculated for the core filled with standard 8.5 w/o fuel only. Afterwards two cases were considered: in the first standard 8.5 w/o fuel elements in individual ring are replaced by LEU fuel elements, in the second standard 8.5 w/o fuel elements in individual ring are replaced by standard 12 w/o fuel elements: from one to all elements in the ring. This is done for all rings.

We can see from Figure 1 that \( f_{hr} \) is maximal when only one element is inserted in B ring. The power of this element would be \( \sim 2.1 \) times bigger than the core average. If more than one LEUs are inserted in B ring, \( f_{hr} \) is reduced but not significantly. Approximately the same conclusions apply also if LEUs are inserted in C ring. Only when they are inserted in D ring, \( f_{hr} \) approaches but still exceeds uniform core value of 1.4. However, \( f_{hr} \) is not found in the centre (B ring) but at LEU fuel elements in D ring. When LEUs are inserted in E or F ring, \( f_{hr} \) becomes lower than in uniform core, because higher power at the core periphery tends to flatten the overall reactor power distribution.

Note that in the worst case (one LEU in B ring in otherwise 8.5 w/o fuelled core) the power of LEU is 2.1 times the average, or 50 % higher than in an uniform core.

Calculated values of \( f_r \) are presented in Figure 2. It can be seen that the peak location is in all cases, except for the E and F rings, in the LEU element. It is interesting to note that \( f_r \) is almost independent on the loading pattern in individual ring.
Figure 1. $f_{hr}$ as a function of LEU location in mixed core with 8.5 w/o standard fuel. Various symbols correspond to different core loading: 1 denotes one LEU element in the corresponding ring, 6 denotes six equidistant LEU elements in the corresponding ring, all denotes all positions in the corresponding ring filled with LEU elements.

Note that in the worst case (one LEU in B ring), the maximum power density in this element reaches $\approx f_{tot} = f_z f_r = 1.25 \times 3.1 = 3.9$. As $f_r$ appears at the fuel rod outer radius (see Figure 5), it is particularly important for pulse analysis.

Figure 2. $f_r$ as a function of LEU location in mixed core with 8.5 w/o standard fuel. Various symbols correspond to different core loading: 1 denotes one LEU element in the corresponding ring, 6 denotes six equidistant LEU elements in the corresponding ring, all denotes all positions in the corresponding ring filled with LEU elements.
When 12 w/o standards fuel elements are inserted in the 8.5 w/o fuel core, the $f_{hr}$ values are much lower than in case of LEU elements but are still much higher than uniform core values for filling B and C ring. Calculated values $f_{hr}$ are presented in Figure 3, from which similar conclusions as in case of LEUs can be made, with the exception of D ring, in which $f_{hr}$ is almost the same as in uniform core.

![Figure 3](image)

Figure 3. $f_{hr}$ as a function of 12 w/o standard fuel location in mixed core with 8.5 w/o standard fuel. Various symbols correspond to different core loading: 1 denotes only one 12 w/o standard fuel element in the corresponding ring, 6 denotes six equidistant 12 w/o standard fuel elements in the corresponding ring, all denotes all positions in the corresponding ring filled with 12 w/o standard fuel elements.

$f_r$ values as a function of 12 w/o standard fuel location are presented in Figure 4. As in previous cases $f_r$ attains its maximal value when only one standard 12 w/o fuel element is in B ring. It is interesting that $f_r$ in C ring is maximal when C ring is completely filled with 12 w/o fuel elements and not when there is only one 12 w/o fuel element, as in the case of LEU fuel.
Figure 4. $f_i$ as a function of 12 w/o standard fuel location in mixed core with 8.5 w/o standard fuel. Various symbols lines correspond to different core loading: 1 denotes only one 12 w/o standard fuel element in the corresponding ring, 6 denotes six equidistant 12 w/o standard fuel elements in the corresponding ring, all denotes all positions in the corresponding ring filled with 12 w/o standard fuel elements.

Figure 5: Power density distribution (rel. units) in mixed core with 8.5 w/o standard fuel and 6 LEU fuel elements in the C ring. The numbers on x and y axis are distances from the centre of the core in cm.
5 CONCLUSIONS

It can be concluded that use of LEU and standard 12 w/o fuel elements in the core filled with standard 8.5 w/o fuel elements in B or C rings should be treated with care, regardless to their loading pattern inside the ring. Use in ring D is less restrictive, provided that the ring is mainly filled with LEUs or standard 12 w/o fuel elements. Use of LEU or standard 12 w/o fuel elements in outer rings (E and F) is always acceptable as it even reduces the $f_{hr}$ factor with respect to the uniform core due to more flat power distribution. In this case, the power peaking does not appear in LEU or standard 12 w/o fuel, but it is found in B ring, which is filled with standard elements. The detailed power peaking analysis in mixed cores is particularly important for pulsing as the maximum pulse temperature distribution roughly corresponds to power density distribution.

REFERENCES


