Calculation of Spatial Weighting Functions for Ex-Core Detectors of VVER-440 Reactors by Monte Carlo Method

Tamás Berki
Institute of Nuclear Techniques
Műegyetem rkp. 9., H-1111, Budapest, Hungary
berki@reak.bme.hu

ABSTRACT

The signal of ex-core detectors depends not only on the total power of a reactor but also on the power distribution. The spatial weighting function establishes correspondence between the power distribution and the detector signal. The weighting function is independent of the power distribution. The weighting function is used for detector-response analyses, for example in the case of rod-drop experiments. [1]

The paper describes the calculation and analysis of the weighting function of a VVER-440. The three-dimensional Monte Carlo code MCNP is used for the evaluation. Results from forward and adjoint calculations are compared. The effect of the change in the concentration of boric acid is also investigated.

The evaluation of the spatial weighting function is a fixed-source neutron transport problem, which can be solved much faster by adjoint calculation, however forward calculations provide more detailed results. It is showed that the effect of boric acid upon the weighting function is negligible.

1 INTRODUCTION

The power control of VVER-440 reactors is based on the signals of ex-core detectors. These ex-core detectors are ionization chambers by type, and they are located in the wall of the biological shield. Nevertheless, the detector signal contribution of individual assemblies depends not only on the power of the assembly but also on their position in the reactor core. The contributions of inner assemblies are lower by several orders of magnitude than that of peripheral assemblies. The contribution has also an axial dependence. This is the reason why the signal of ex-core detectors depends on power distribution, while the total power of the reactor is constant.

The spatial weighting function is used for the description of the contribution of an arbitrary volume of the reactor core to the detector signal. Knowledge of the weighting function makes the reactor operators’ job easier. For example, rod drop reactivity measurement data become more easily interpretable.

There are different ways to define the above weighting function. In this paper, the value of the weighting function means the number of $^3\text{He}(n,p)^3\text{H}$ reactions in the ex-core detector caused by a fission neutron that has been born in the point $r$ of the core. The weighting function is defined in this way because in this paper a $^3\text{He}$-filled ionization chamber, type KNK-4, is examined. If the spatial weighting function is known, the detector signal can be calculated. The signal of the detector is given by:
\[ D = C \int_{V} w(\mathbf{r})q(\mathbf{r})dV \]  

(1)

where \( w \) is the weight of a point of the reactor core, \( q \) is the power density being in direct proportion to the source strength of fission neutrons, \( V \) is the volume of the core and \( C \) is a suitable constant.

## 2 CALCULATION OF THE SPATIAL WEIGHTING FUNCTION

There are several different methods in use to calculate the weighting function. Calculations with point-kernel method [2] and with method of discrete ordinates [3] can also be found in the literature. In this work, the Monte Carlo method is applied. MCNP4C Monte Carlo N-Particle Transport Code is used for the calculations [4]. The weighting function is calculated with both the forward and adjoint Monte Carlo method. Since the calculation of the weighting function is a fixed source problem, the adjoint method is much faster than the forward, but the forward method gives more detailed results. It is possible to calculate the value of the weighting function in one given point with the forward method, however a long calculation is necessary to determine the weight of each point of interest. With the aid of the adjoint method it is not possible to calculate the weight of a given point, but only of a finite volume. Furthermore, it is necessary to use other simplifications when applying the adjoint method.

### 2.1 Calculational Model

The geometry and composition of materials of the reactor and its environment are modelled in the finest possible detail. There are three pieces of the examined KNK-4 neutron detector around the reactor. These detectors are located symmetrically by 120 degrees. Since the geometry of the reactor has also a rotational symmetry of 120 degrees, modelling only one detector and the corresponding sector of the reactor is sufficient. Considering that the weighting function is symmetrical to the axis that links the centre of the reactor with the detector, only half of the area in interest is modelled. In this way, the lighter shaded assemblies on the left side of Figure 1 constitute the examined region, on which the weighting function is calculated. A detailed, pin level model is used for the forward calculation. The model of an assembly and a part of the core mantle are illustrated on the right side of Fig. 1.

![Figure 1: The applied model](image-url)
### 2.2 Forward calculation [5]

In the course of the forward calculation, the value of the weighting function is calculated “point by point”. The reactor core is divided into ten horizontal layers with equal heights. Neutrons are started from individual tenths of length of fuel rods with Watt’s energy spectrum. Tenths of rods are selected uniformly from the examined region. The generated $^3$He(n,p)$^3$H reactions are counted in the sensitive volume of the detector. MCNP makes it possible to “switch off” neutron production following fission (NONU card; $\nu$=0), therefore the code directly yields the weight of the given tenth of a rod. In our work altogether 1080 weights of tenths of rods have been calculated. ENDF/B-VI based continuous energy cross section libraries, part of the MCNP package, have been used for the calculations. Finally, analytical functions have been fitted onto the calculated values. In this way, a three dimensional spatial function has been obtained. A vertical section of the fitted function, in the 5th tenth from above, is shown in Figure 2.

![Figure 2: The fitted weighting function obtained from the forward calculation](image)

### 2.3 The adjoint Calculation

A further goal of our work is the evaluation of how the weighting function depends on other parameters of the reactor. For example, the power of the reactor has influence on the density of water, which may cause significant influence on the weighting function. Since the forward calculation of the weighting function is very time-consuming, a faster method should be chosen. Thus, the adjoint Monte Carlo method is used for further calculations.

With the adjoint method, the weight of a given point cannot be calculated. It is also difficult to take the geometry into consideration as detailed as in the forward calculation. Moreover, a multigroup cross-section library has to be used instead of continuous. For these reasons, results obtained from adjoint calculations are less accurate, but this method is much faster compared to the forward one.
In the course of the adjoint calculation, the reactor core is divided into 20 equal, horizontal layers. Weights of twentieth of assemblies are calculated. The pin level model of fuel assemblies is replaced with a homogenous one. The adjoint calculations are also made using MCNP4C [6]. A 44 group, ENDF/B-VI based cross-section table is applied, which is generated with CSAS and XSDRMP modules of SCALE [7]. Figure 3 shows the calculated weights of the 11th twentieth from above of the assemblies. The hexagons represent the weights of the assemblies.

Figure 4 shows a coordinate system, which is used to identify the assemblies. Assemblies are signed with these coordinates in the remaining part of the paper. The axial change of weights in the assembly (5;6) is illustrated in Figure 5.

Figure 3: Decimal logarithm of weights of twentieths of assemblies in the 11th layer

Figure 4: Coordinate system to identify assemblies
2.4 Evaluation of the Results

In view of these figures it appears that the signal of the detector is principally caused by neutrons that had been born in the four assemblies closest to the detector. It is important to note that the contribution of detector signal is given by the weight multiplied by the source strength of fission neutrons. Considering that the latter one does not change orders of magnitude inside the reactor core, it can be concluded that the ex-core detectors are quite insensitive to the flux-distribution in the central part of the reactor core. These results are confirmed by other publications of the literature. [2,3]

The axial distribution of the weights shows that a central twentieth of an assembly has about one order of magnitude higher weight than the uppermost and the lowermost twentieth. This ratio is more than ten in the case of a peripheral assembly, and it is less than ten in the case of an inner one. By analysing Figure 5 it can be observed that the curve is slightly asymmetrical. This is due to the fact that the axial position of the detector is a little lower than the midplane of the reactor (as is the maximum of the neutron flux).

To compare results obtained from forward and adjoint calculations, weights of tenths of assemblies are calculated with the aid of the continuous weighting function. The weight of a tenth of an assembly, using the weighting function or the weights of tenths of fuel rods, can be calculated using this formula:

\[
W = \frac{1}{Q} \int_{\text{tenth of assembly}} w(r) f(r) dV = \frac{\sum_{i=1}^{126} w_i q_i}{\sum_{i=1}^{126} q_i}
\]  

(2)

Figure 5: Weights in the assembly (5;6)
where $Q$ is the power of the given tenth of assembly, $w_i$ is the weight of the $i^{th}$ tenth of fuel pin and $q_i$ is the power of the $i^{th}$ fuel pin. Summing is up to 126 because there are 126 rods in an assembly of VVER-440.

Table 1 contains a comparison of weights of some tenths of assemblies calculated with the adjoint method and with the aid of the continuous weighting function.

Table 1: Comparison of weights obtained from forward and adjoint calculation

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Tenth (counted from above)</th>
<th>Weight from forward calculation</th>
<th>Weight from adjoint calculation</th>
<th>Relative difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(5;6)</td>
<td>3</td>
<td>3.77E-7</td>
<td>3.48E-7</td>
<td>-7.69</td>
</tr>
<tr>
<td>(5;6)</td>
<td>6</td>
<td>1.16E-6</td>
<td>1.11E-6</td>
<td>-4.31</td>
</tr>
<tr>
<td>(5;6)</td>
<td>10</td>
<td>1.66E-7</td>
<td>1.52E-7</td>
<td>-8.43</td>
</tr>
<tr>
<td>(4;7)</td>
<td>3</td>
<td>3.77E-7</td>
<td>3.51E-7</td>
<td>-6.90</td>
</tr>
<tr>
<td>(4;7)</td>
<td>6</td>
<td>1.09E-6</td>
<td>1.07E-6</td>
<td>-1.83</td>
</tr>
<tr>
<td>(4;7)</td>
<td>10</td>
<td>1.72E-7</td>
<td>1.63E-7</td>
<td>-5.23</td>
</tr>
<tr>
<td>(4;6)</td>
<td>6</td>
<td>2.06E-7</td>
<td>1.40E-7</td>
<td>-32.04</td>
</tr>
<tr>
<td>(4;6)</td>
<td>10</td>
<td>3.36E-8</td>
<td>2.26E-8</td>
<td>-32.74</td>
</tr>
<tr>
<td>(3;7)</td>
<td>6</td>
<td>1.92E-7</td>
<td>1.48E-7</td>
<td>-22.92</td>
</tr>
<tr>
<td>(3;7)</td>
<td>10</td>
<td>3.52E-8</td>
<td>2.78E-8</td>
<td>-21.02</td>
</tr>
<tr>
<td>(3;6)</td>
<td>6</td>
<td>3.54E-8</td>
<td>1.80E-8</td>
<td>-49.15</td>
</tr>
<tr>
<td>(3;6)</td>
<td>10</td>
<td>7.30E-9</td>
<td>3.91E-9</td>
<td>-46.44</td>
</tr>
</tbody>
</table>

It can be concluded that weights calculated with the adjoint method are lower than those calculated with the forward method. The relative difference of weights obtained using the adjoint and forward method is low in the case of peripheral assemblies; the difference increases towards the centre of the reactor. The difference does not depend on the axial position of the tenth inside a given assembly.

The cause of the deviation will be a subject of follow investigation. The main cause of the difference can be that different cross-section libraries are used for the forward and the adjoint calculations. Another reason can be that a lot of simplifications have been applied during the cross-sections processing with SCALE. Moreover, the MCNP geometry of the adjoint calculation is also simpler than that of the forward calculation.

The time required to complete the adjoint calculation is about the thirtieth of that required by the forward one.

3 EXAMINATION OF THE EFFECT OF CONCENTRATION OF BORIC ACID

The effect of the change of the concentration of boric acid was also investigated. Only those neutrons can reach the ex-core detector, which have sufficiently high energy in the reactor core; furthermore, the absorption cross section of $^{10}$B is high only in the thermal region. Consequently, the boric acid could not have strong effect upon the weighting function.
In order to evaluate the influence of the boric acid on the weighting function, a second weighting function is calculated with no boric acid present in the cooling water. The adjoint method is used for the calculation with the same conditions described in Section 2.3. Figure 6 presents the change of weights when the boric acid is removed from the water. The logarithms of weights, calculated with no boric acid in the water, have been subtracted from the logarithms of weights, calculated with boric acid present in the water. The numbers in the figure mean the difference of the decimal logarithms of the weights, which is the same as the logarithm of the ratio of the weights.

Figure 6: The effect of boric acid on the weights. (The logarithms of the ratio of the weights with and without boric acid.)

According to the calculation, the absence of boric acid has significant effect only upon the weights of inner assemblies. Considering that the weights of these assemblies are far lower than those of peripheral ones, it can be concluded that the effect of boric acid is negligible. This result is also confirmed by Ref. [3]. It is not clear why the weights of the inner assemblies decrease when boric acid is absent.

4 SUMMARY

In this paper the spatial weighting function for KNK-4 ex-core detectors, which are used in VVER-440 reactors, is calculated and evaluated. The weighting function is calculated with forward and adjoint Monte Carlo method. It is shown that the contribution of the ex-core detector signal is mostly given by neutrons that are born in the assemblies closest to the detector. The concentration of boric acid has significant effect on the weights of inner assemblies only; therefore, the concentration of boric acid practically has no effect on the detector signal.

The weighting function cannot be measured directly. However, the detector signal can be calculated using the weighting function and it can be measured too. Comparison of the detector signal that has been calculated with the aid of the weighting function with measured data of a rod-drop experiment is in progress.
REFERENCES


