CALCULATION OF SPATIAL WEIGHT FUNCTIONS FOR VVER-440 EX-CORE NEUTRON DETECTORS

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ABSTRACT

The objective of the work presented in this paper was the determination of a spatial weight function for VVER-440 ex-core detectors to be used for the interpretation of reload startup rod drop measurements. In view of the complexity of the geometry of the core as well as the detector, furthermore the presence of a cavity between the vessel and the concrete shield, Monte Carlo calculations were applied. In spite of the fact that in the corresponding literature the use of adjoint methods dominates, in the present case the forward method was chosen and implemented using MCNP4C. The application of the forward method made it possible to avoid the approximations which stem from the homogenization of the cross sections of the assembly material and from the use of group-wise data. MCNP calculations were performed to determine the reaction rate, which is caused by a neutron born in a tenth of a pin at Watt spectrum, in the ^{3}He filled KNK-4 type ionization chambers. In the calculations all the geometrical details and material compositions were modelled to the highest accuracy. In order to reach sufficiently low (less than 1%) standard deviation within reasonable time, quite a few variance reduction methods were tried, of which the weight window method proved most suitable. Having obtained the MCNP results, a three-dimensional third order exponential polynomial function was fitted onto the points (tenth of pins). The results show that the major part of the signal of the VVER-440 ex-core detectors is due to neutrons originating in less than 20 assemblies being closest to the detectors. At the inner part of the third assembly layer (from the external boundary of the core) the value of the weight function is only 0.05% that of the tenth of pin closest to the detector. Investigations have started to determine the influence of other parameters, such as burnup, fuel and moderator temperatures on the weight function.

1. INTRODUCTION

The power regulation system of VVER-440 reactors is based on the signals of the ex-core neutron detectors located in the wall of the biological shield. It is known, however, that the contribution of the fuel assemblies to the response of these detectors does not only depend on the power, but also on the position of the given assembly in the core. The weight of the inner assemblies is several orders of magnitude lower than that of the outer ones. There is also a spatial dependence in axial direction. Therefore, the signal of the ex-core detectors for a given reactor power is strongly influenced by the spatial power distribution and, indirectly, by the parameters which determine the distribution, such as load pattern, time elapsed in the cycle, position of the control assemblies etc.

The contribution of a given part of the core, i.e. an assembly, a fuel rod or a portion of a rod, to the ex-core detector signal, as a function of the position of the given part, is usually described by the so-called spatial weight function. The accurate knowledge of the spatial weight function can be very beneficial for the solution of various reactor operational and safety problems. For example, it can help the proper interpretation of the startup reactivity measurements, i.e. the determination whether the detector signal measured during the rod-drop experiment carried out on the refuelled reactor supports the reactivity value determined earlier by the load pattern calculations[1]. Another important application of the weight function may be the safety analysis of the reactor. For example, the elaborate weight function may help to investigate how effectively certain transients which cause a sudden change in the power density distribution (such as a boron dilution accident) can be detected using the ex-core ionization chambers. It will also be examined in the future whether more information may be obtained for the shape of the power density function, with special regard to the potential irregularities, by changing the positions of the ex-core detectors in vertical direction.

The weight function can be defined in various ways. In our case the weight function is a multivariable function which gives the average number of ^{3}He(n,p)^{3}H reactions in the ex-core detector for one fission neutron born with Watt-spectrum in a tenth of a fuel pin in different core positions.

2. METHOD OF CALCULATION

In view of the fact that the geometry of the space between the fuel pins and the ex-core detectors is rather complicated, reliable calculation of the neutron transport could only be performed using a technique for which modelling of the geometry is not problematic. Accordingly, the program MCNP4C [1] was chosen as such.

Calculation of the weight function with the Monte Carlo method is not novel. Even the application of MCNP for the determination of the weight function of VVER-440 reactors is reported in the literature [2]. For several reasons, however, contrary to the method used there (adjoint Monte Carlo), the forward method was chosen for the calculations described in this paper. For example, the errors due to the homogenization of the assembly and the use of group-wise data could be avoided in this manner.

The application of the forward method to the determination of the above defined weight function is also evident in the case of MCNP since this program makes it possible to switch off the tracing of fission neutrons from fission reactions. In this way, by calculating the transport of neutrons born in tenths of fuel pins with Watt spectrum to the ex-core detectors directly yields the values of the weight function. Nevertheless, one must remember that the actual signal of the detector is calculated as the spatial integral of the product of the weight function and the fission density over the whole core region in interest. Quite obviously, the fission density distribution has to be determined in an independent calculation.

However, it is again important to note that the function shown is the weight function only and the contribution of a region to the detector signal is calculated as the spatial integral of the product of the weight function and the fission density.

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[1] The work described in this paper was initiated by a demand of just this kind, i.e. for a weight function to help the proper interpretation of the startup reactivity measurements at Paks NPP.

3. CALCULATIONAL MODEL

Since the objective of the calculations was the determination of the weight function at high accuracy, the reactor core, the space between the core and the detector and the detector itself had to be modelled in the finest possible details, both in terms of geometry and material composition.

With respect to the primary goal, i.e. the determination of the weight function for the KNK-4 ionization chambers, which are used for the startup reactivity measurements, furthermore to the fact that these three detectors are located symmetrically, it was sufficient to model one detector and the core region in its vicinity. The horizontal section of the model set up is shown in Fig. 1. The model extends to the region from which the expected contribution is not negligible. Due to symmetry reasons it was not necessary to study contributions from both sides of the symmetry axis. In the figure those assemblies are denoted, from which neutrons were not started, but they were present in the model due to their neutron scattering effects. These assemblies are the ones on the right hand side of the symmetry line.

The above defined weight function is obviously detector dependent, thus it was crucial to set up a proper detector model. The KNK-4 type detector is made up of two volumes: a ^{3}H filled neutron sensitive volume at 3 bar pressure and a ^{4}H filled region for gamma compensation. The regions are concentric cylindrical rings, the neutron sensitive part being outside. The MCNP detector model shown in Fig. 2 have been created based on the information available about the detector.

4. VARIANCE REDUCTION METHODS APPLIED

The entire model set up for the calculations is rather large, i.e. the source to detector distance is several times larger than the mean free path of fast neutrons. Therefore, in order to achieve satisfactory Monte Carlo statistics it was necessary to exercise variance reduction techniques. The advantages and disadvantages of the following options offered by MCNP were looked at in order to find the optimal strategy:

- use of energy cutoff;
- application of a spatial importance function in the space between the reactor core and detector, particularly with the aid of cylindrical surfaces of vertical axis and horizontal and vertical planes;
- source energy bias;
- directional bias of source neutrons;
- the weight window game.

Summarizing the results it can be concluded that, although use of the first four methods resulted in some degree of increase in efficiency, the most dramatic change occurred when the method of weight windows was utilized. At the same time, it is important to note that a vital condition for the good performance of the weight window game is the proper choice of the boundaries of the importance regions, in both space and energy.

Trials to bias the direction of the source neutrons lead to the observation that a great degree of biasing causes unacceptable fluctuations in the variance of the variance. Using an exponential bias, the optimum value of the constant in the exponent turned out to be 0.6.

By utilizing the above variance reduction techniques the statistical uncertainty could be reduced to as low as 1% (in most cases lower), even in the case of the farthest away source pins.

5. CALCULATIONAL RESULTS

The paper presents the calculational results obtained for the layer of tenths of fuel pins, which are situated immediately above the horizontal symmetry plane of the core. The tenths of fuel pins were selected in such a manner that they cover the model shown in Fig. 1 in an even lattice. On the average, 5 or 6 tenths of fuel pins were calculated for each assembly, with the exception of the assembly being closest to the detector, for which 19 pins were selected. After the calculations had been completed for an assembly, the obtained results were analyzed and new weight windows were generated for the next assembly. Altogether 159 tenths of fuel pins were calculated.

In order that the calculational results be easier to handle, more transparent, and the reliability could be tested, efforts have been made to fit an analytical function onto the single weight function values. The fitting was performed using an own program, which had been developed for multi-dimensional regression and based on the method of flexible polyhedra [3]. The first step of the fitting task was to find the optimal two-dimensional frame of reference. Three types of systems were tested, out of which the best turned out to be a Cartesian frame of reference, whose x axis is directed from the center of the reactor to the axis of the detector and the perpendicular y axis intersects the x axis at 130 cm from the center of the reactor.

The function to be fitted was in all trials a polynomial of second or third order with two variables. The fitting was done on the logarithm of the weights using the weighted least squares method. The weighting factors were calculated from the variance of the MCNP calculated values. Therefore, the values of lower uncertainty had a larger weight in the fitting.

The figure of merit of the fitted function was calculated in two ways: (1) the minimum value of the weighted square of differences; (2) sum of the absolute values of the differences between the MCNP calculated and function derived data.

The best fit was obtained using a polynomial of the following type:

$$S(x,y) = \exp(c_1 + c_2 \cdot x + c_3 \cdot y + c_4 \cdot x^2 + c_5 \cdot x \cdot y + c_6 \cdot y^2 + c_7 \cdot y^3), \qquad (1)$$

where $S(x,y)$ is the spatial weight function.

The coefficients c_1 ... c_7 obtained for the fit onto the 159 points are listed in Table 1.

The function is shown in graphical representation for the modelled region in Fig. 3. The contour lines show the 10 base exponent of the weight function (i.e. the order of magnitude of the detector weight). It is very informative to see that the major part of the detector signal is attributed to a few assemblies, which are located closest to the detector. At the inner part of the third assembly layer (from the external boundary of the core) the value of the weight function is only 0.05% that of the tenth of pin closest to the detector. However, it is again important to note that the function shown is the weight function only and the contribution of a region to the detector signal is calculated as the spatial integral of the product of the weight function and the fission density.

Table 1. c_i coefficients obtained from fitting onto 159 points.

Coefficient	**Value**
c_1	-1.1509E+01
c_2	1.3597E-01
c_3	6.8451E-04
c_4	3.1520E-04
c_5	1.6951E-05
c_6	-2.0893E-04
c_7	3.6629E-06

6. SUMMARY

The accurate knowledge of the spatial weight function for the signal of the ex-core detectors can be very beneficial for the solution of various reactor operational and safety problems. The calculations presented in this paper aimed at the determination of such a function indicate that, with the aid of the MCNP code, the function can be computed at a tenths-of-pins level even within a statistical uncertainty of 1% at acceptable (though massive) CPU time requirement. According to the results already obtained the major part of the signal of the VVER-440 ex-core detectors is due to neutrons originating in less than 20 assemblies being closest to the detectors.

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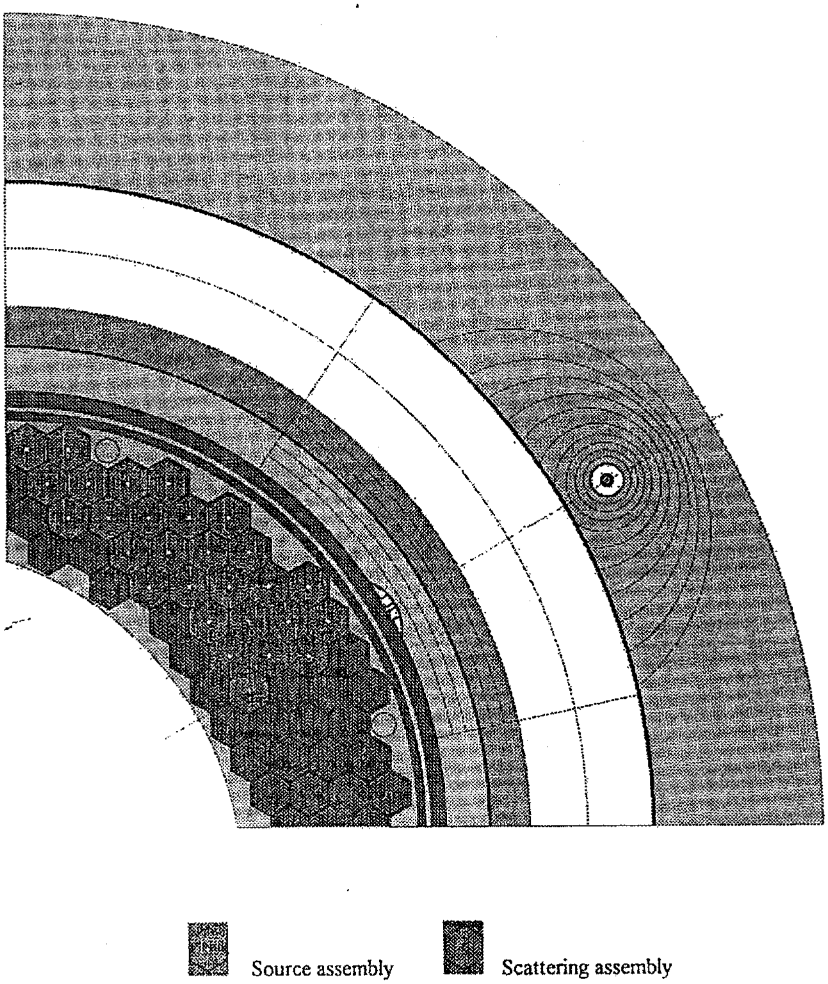

Figure 1. Horizontal section of the MCNP model

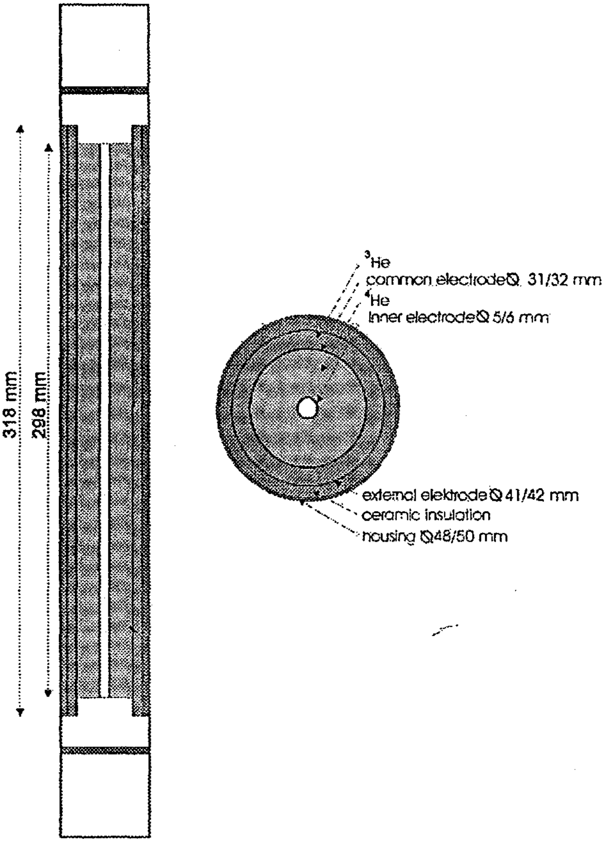

Figure 2. Vertical and horizontal sections of the MCNP model of the KNK-4 detector

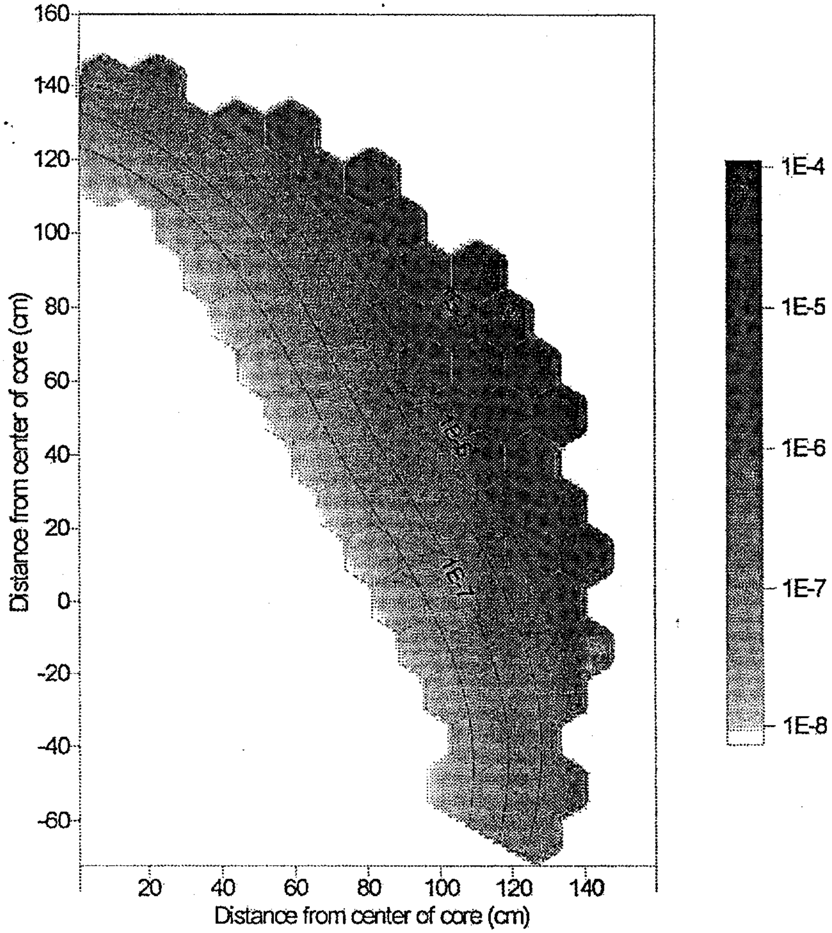

Figure 3. Two dimensional map of the spatial weight function (for the layer of tenths of fuel pins, which are situated immediately above the horizontal symmetry plane of the core)