

NEUTRONIC CALCULATION SYSTEM FOR CANDU CORE BASED ON TRANSPORT METHODS

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Abstract. This paper is intended to highlight a global neutronic calculation system by using it to estimate the neutronic effect of the adjuster rod system insertion in the CANDU Standard core. The calculation system WIMS_PIJXYZ_LEGENTR is based on transport methods and was developed in the Institute for Nuclear Research Pitesti. By using only transport codes the mentioned multigroup calculation system is both coherent and consistent. In the same time, it allows a good representation both for CANDU cell/supercell and core. These conditions are compulsory in the CANDU reactor core types, for solving the problems which arise from the strong heterogeneities mainly due to the perpendicular insertion of the reactivity/control devices by the fuel channels. Herein this calculation system is used for performing the global neutronic parameters for a CANDU reactor core which has the adjuster rod system inserted. More exactly, a CANDU Standard core with fresh fuel at nominal power is taken into consideration. To emphasize this calculation system a comparative analysis of its performed results obtained in two calculation ways: using the macroscopic cross sections homogenized on each cell (the homogenized case) and with the cross sections for each material (the heterogeneous case). Also it is made a comparison with the similar ones obtained with the WIMS_PIJXYZ_DIREN calculation system, where the macroscopic cross section are homogenized on each cell. The comparative analysis shows a good agreement between these estimated results.

Key words: CANDU Standard core, adjuster rod system, neutronic parameters.

1. INTRODUCTION

The global neutronic parameters of a reactor depend on the used calculation methodology and mainly on the way to generate the effective multigroup constants. This is the reason why the knowledge of the techniques for obtaining multigroup constants libraries from nuclear data libraries, and from these to collapsed constants, implies important efforts for each reactor type.

Each calculation methodology (or system) must consist of codes and additionally of proper nuclear data libraries, cell/supercell and core models, recommendations regarding the input data and specification about the output data interpretation.

The solution for this difficult problem was tackled in two ways. The first is related to the use of some strong approximations (exclusively bigroup diffusion calculations), with the compensation of these approximations by codes calibration with empirical parameters (obtained experimentally). The second is related to the use of a nuclear library dedicated to a reactors type (fast or thermal) and in the same time to the use of some higher order approximations.

For estimating the global neutronic parameters for CANDU reactors type, the AECL uses the classical calculation system named PPV_MULTICELL_RFSP, which is based on the PPV, MULTICELL and RFSP codes, [1,2,3]. The PPV_MULTICELL_RFSP system pertains to the calculation systems which are based on strong physical approximations and on experimental adjustments. It is based on the Wescott convention, solving the diffusion equation and experimental adjustments. The main success of this calculation system is related to the assessment of the refueling process and is due mainly to its rapidity. After more 30 years experience of CANDU reactor operating, it seems to show that these procedures work and the results can satisfy the design requirements.

In the Institute for Nuclear Research Pitesti (INR) there were developed two calculations systems for neutronic analysis simultaneously with the usage of the classical AECL calculation system: WIMS_PIJXYZ-DIREN, [4], and WIMS_PIJXYZ_LEGENTR, [5]. These systems are based on transport WIMS and PIJXYZ codes, [6] and [7], for generation and respectively the adjustment of the cross sections and LEGENTR and DIREN codes [8] and [9] for estimating the global neutronic parameters by transport and respectively diffusion methods. They were aligned with the INR effort for developing its own calculation methodology, an alternative for the classical AECL one. The goal of this effort is related to an independent way for verifying the important calculations, to perform reference calculations as well as a detailed knowledge of the reactor physics problems.

The objective of this paper is to summarize the calculation system WIMS_PIJXYZ_LEGENTR and to highlight it in performing the global neutronic parameters for the CANDU Standard core with the adjuster rod system inserted in.

The WIMS_PIJXYZ_LEGENTR system is used to calculate the global neutronic parameters for a fresh CANDU Standard core at nominal power. The core contains NU_37 fuel bundles (Natural Uranium, 37 elements) and the considered reactivity device is the adjuster rod system, [10]. The estimated global neutronic parameters are: K-eff. values, the adjuster rod system reactivity worth and the flux distributions. The WIMS_PIJXYZ_LEGENTR calculations are approached in two ways: using macroscopic cross sections homogenized on each cell (the homogenized case) and using macroscopic cross sections for each material from all cells (the heterogeneous case).

Here in, it is presented a comparative analysis of the results obtained by these two approaches and in the same time a comparison with the similar results performed with the WIMS_PIJXYZ_DIREN calculation system.

2. SHORT PRESENTATION OF THE WIMS_PIJXYZ_LEGENTR CALCULATION SYSTEM

In Fig. 1 the diagram of the WIMS_PIJXYZ_LEGENTR calculation system is shown. Starting from a 69-groups ENDF/B-V based library, the WIMS_PIJXYZ_LEGENTR system is based on three transport codes: (1) the standard lattice-cell code WIMS used for macroscopic cross sections generating in supercell option; (2) PIJXYZ code, for 3D simulation of the reactivity devices and adjustment of these cross sections, in other words obtaining the incremental cross sections for reactivity devices; (3) LEGENTR 3D transport code, for global neutronic parameters calculations.

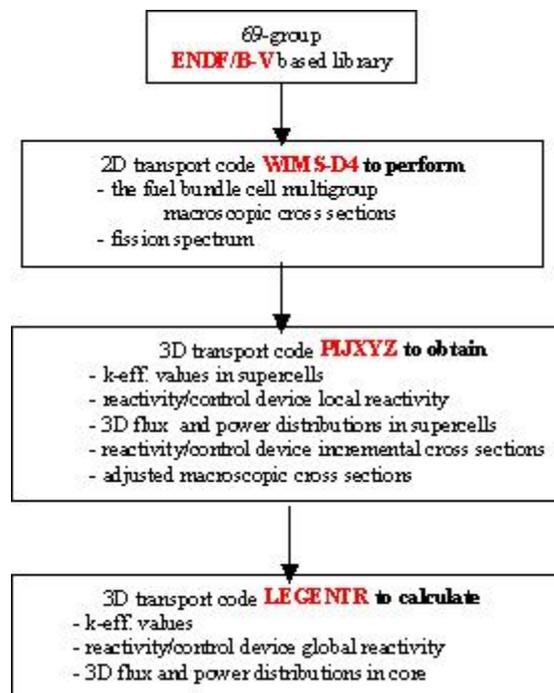


Fig. 1 – The WIMS_PIJXYZ_LEGENTR calculation system diagram.

Both PIJXYZ and LEGENTR codes were developed in INR. PIJXYZ is a 3D integral transport code using the first collision probability method and it has been developed for CANDU cell/supercell geometry. It is consistent with WIMS lattice-cell calculations and allows a good geometrical representation of the CANDU bundle in three dimensions. LEGENTR is a 3D S_N transport code based on projectors technique and it can be used both for 3D supercell and 3D core calculations.

While the WIMS code is widely known and used, in the following, a brief presentation of the PIJXYZ and LEGENTR codes, which were developed in INR, must be made in the following.

PIJXYZ is a 3D integral transport code based on first collision probabilities method. It has been developed for CANDU cell/supercell analysis, where the reactivity devices are inserted perpendicular to the fuel channels. It is similar to SHETAN code [11]. Thus, a mixed rectangular-cylindrical coordinate system is used for a suitable geometrical representation. Taking into account the large memory and long execution time requirements, the code uses a combination of classical collision probabilities method (CP) and interface currents method (IC). This method is named “block method” (BM) [12], and it is formulated such that it extends the applicability of CP to the solution of large systems by means of the interface currents technique. BM requires only the collision probabilities between the regions of the same block. Inter-block currents through surface subdivisions couples all blocks. The main approximations of the BM are:

- i) flat flux on each region,
- ii) constant and isotropic local source in each region,
- iii) isotropic in-current on boundary.

PIJXYZ uses vacuum as boundary conditions, with reflective, albedo and fixed in-current distributions.

The LEGENTR code was also developed in INR, using the expertise in treating the steady state CANDU and TRIGA reactor problems [13], [14]. The main idea used in solving deterministic transport equation is to split the phase space in elementary cells. The set-up of the multigroup cross sections, discrete ordinates methods and the spatial grid is the first step in obtaining the transport equation numerical solution. The classical diamond differences DD integration method for solving the S_N transport equation in Cartesian geometries is well known. The numerical integration schema used in the LEGENTR code is obtained by projecting the transport equation from each elementary cell on the 3D spatial coordinates. This way, for each phase space cell an ordinary differential equations system with initial conditions is obtained. Starting from a flat flux inside the cells and null fluxes at the boundaries, the numeric solution is obtained after a number of iterations. The integration method used in LEGENTR leads to accurate results in reasonable calculation times.

3. CALCULATIONS AND GEOMETRIC MODELS

First of all, we mention that in each of the three calculation steps mentioned above, two configurations are taken into consideration: the reference configuration (without any reactivity device inside the supercell respectively in core) and the perturbed one (with the reactivity device inserted into the supercell respectively in core). The considered reactivity system is the adjuster rod system.

The adjuster rod system consists in twenty one adjuster rods (stainless steel absorbers), displayed in three rows of seven and it is used to flatten the power distribution and to provide 30 minutes of xenon override capability (equivalent to ~ 15 mk), [15]. The adjuster rods are used in banks such that the reactivity worth of each bank lies well within the normal control range of the zone control system.

The first step in our calculations is generating the CANDU supercell multigroup macroscopic cross sections with 2D transport code WIMS-D4, with a 69-group ENDF/B-V based library.

The WIMS multicell calculations were performed by solving the transport equation by the collision probability method on 18 energy groups. The used geometric model has two types of cell: fuel cell and reactivity device cell. The considered CANDU supercell consists in one reactivity device cell surrounded by four fuel cells (Fig. 2). For the perturbed supercell the reactivity device cell contains an adjuster rod rounded by D_2O moderator, since for the reference supercell contains only D_2O moderator.

In Fig. 2, the WIMS geometric model of the CANDU supercell is presented.

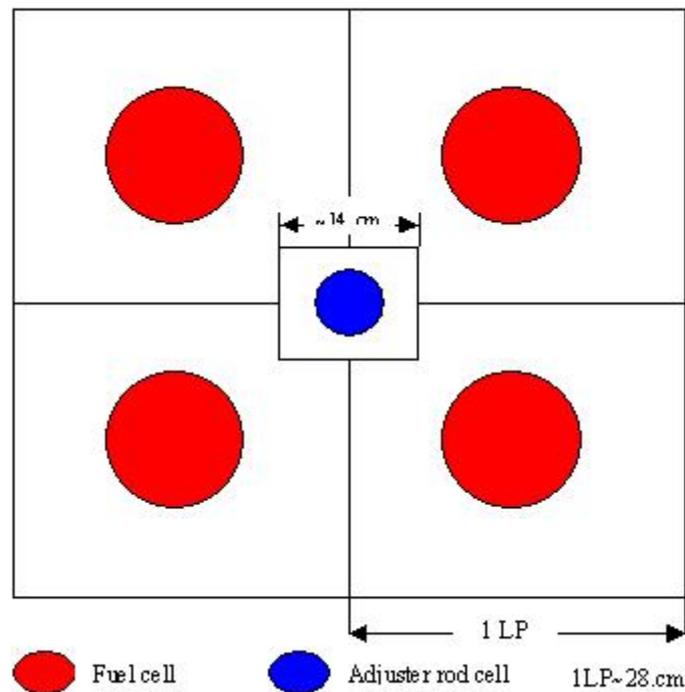


Fig. 2 – The WIMS geometric model for CANDU Standard supercell.

In the WIMS edit routine the macroscopic cross sections for the supercell materials and the fission spectrum are condensed down from 18 to 7 groups.

The second step consists in the PIJXYZ calculations. So, the above macroscopic cross sections and the fission spectrum are used in the input deck of the 3D transport code PIJXYZ for adjustment.

The PIJXYZ calculations are made on 7 energy groups, using reflective boundary conditions. For obtaining relevant results, a fine mesh spacing (both rectangular and cylindrical) it is chosen. So, there were considered 6*6*9 rectangular meshes in each block, 9 axial by 5 radial meshes in fuel cylinder and 6 axial by 6 radial meshes in adjuster rod cylinder, respectively.

The edit PIJXYZ form of the macroscopic cross sections is different for the two cases of global neutronic calculations.

Thus, for the homogenized LEGENTR case and for DIREN calculations it is made a homogenization on each cell type since for the heterogenized LEGENTR case the macroscopic cross sections are calculated for each material in each cell type.

A typical PIJXYZ calculation model in Fig. 3 is shown. The fuel bundle is a horizontal cylinder and the reactivity device is a vertical cylinder. Both are surrounded by moderator. Two different configurations were calculated: one with the reactivity device present (perturbed supercell) and one with the device replaced by moderator (reference supercell).

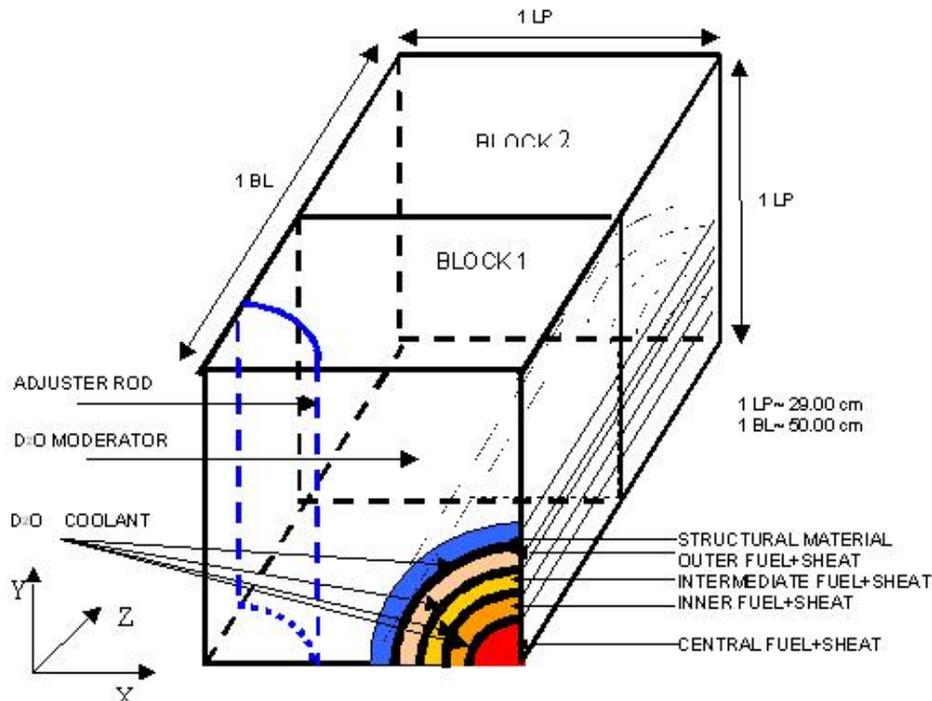


Fig. 3 – The PIJXYZ geometric model for CANDU Standard supercell.

In the third step, the 3D global calculations are performed with LEGENTR code on two energetic groups and on an eighth of the CANDU Standard core, because the adjuster rod system is symmetrically inserted in the core.

For performing accurate flux distributions in the heterogenized LEGENTR calculations 152*152*126 rectangular meshes were considered.

The global reactivity worth of the adjuster rod system is calculated as:

$$\rho = \left(\frac{1}{k_{eff,ref}} - \frac{1}{k_{eff,per}} \right), \quad (1)$$

where: $k_{eff,ref} = k_{eff}$ value in the reference core, and $k_{eff,per} = k_{eff}$ value in perturbed perturbed core.

The layout of adjuster rod system in the CANDU standard core (transversal and axial planes) is shown in Figs. 4 and 5, respectively:

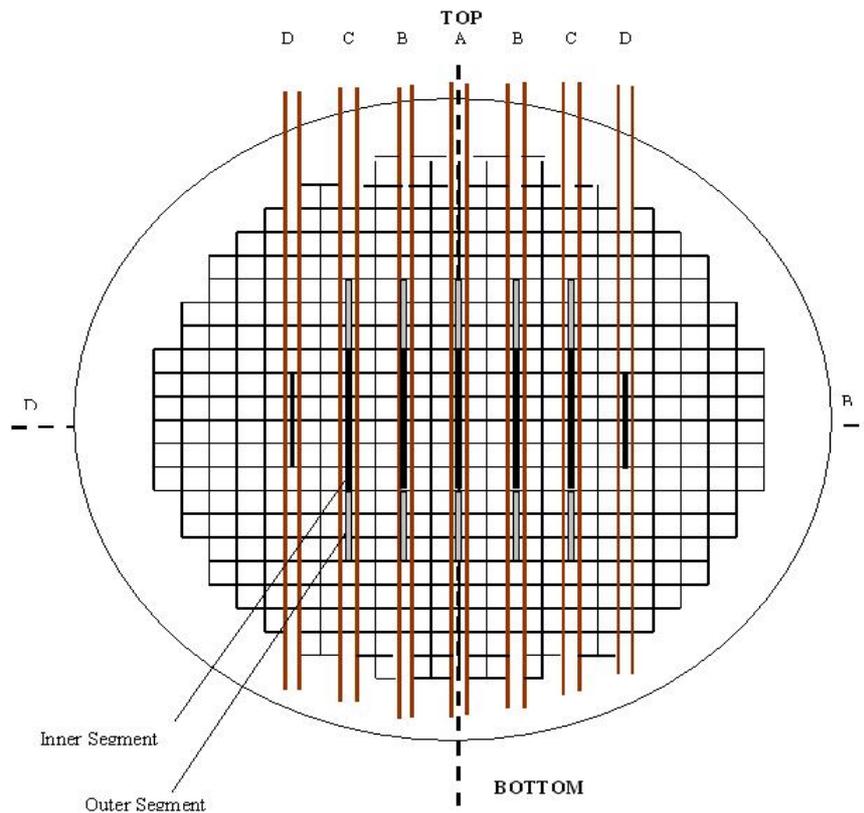


Fig. 4 – The transversal plane of CANDU core with adjuster rod system in.

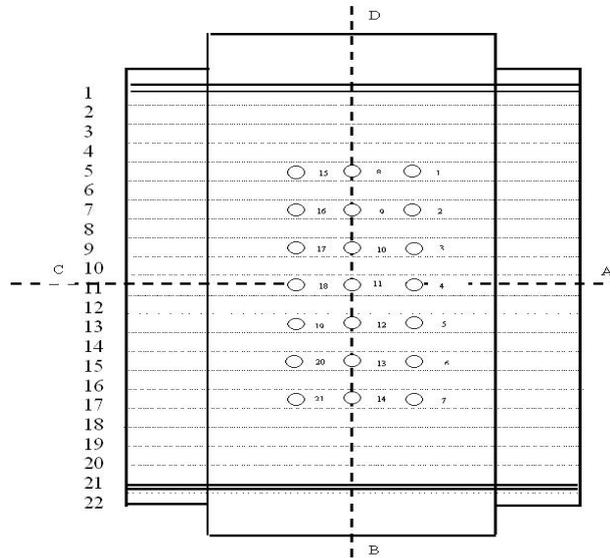


Fig. 5 – The axial plane of CANDU core with adjuster rod system in.

4. RESULTS AND DISCUSSIONS

In the following, the K-eff. global values, the adjuster rod system reactivity worth and the flux distribution are presented to highlight some significant results of the two cases of WIMS_PIJXYZ_LEGENTR calculations (heterogenized and homogenized respectively). These results are compared with the similar ones obtained by the WIMS_PIJXYZ_DIREN calculation system.

4.1. The K-eff. global values and the adjuster rod system reactivity worth

In the Table 1 and respectively Table 2 are listed the K-eff. values for the reference and perturbed configurations and the global rod adjuster system reactivity calculated by the above mentioned manner:

Table 1

The K-eff. values obtained by different calculation methods

CANDU Standard core	The global K-eff. values		
	WIMS_PIJXYZ_LEGENTR heterogeneous	WIMS_PIJXYZ_LEGENTR homogenized	WIMS_PIJXYZ_DIREN
Reference	1.0777	1.0569	1.0527
Perturbed	0.9193	1.0400	1.0348

Table 2

The global reactivity worth of the adjustor rod system

The global adjustor rod system reactivity worth		
WIMS_PIJXYZ_ LEGENTR heterogeneous	WIMS_PIJXYZ_ LEGENTR homogenized	WIMS_PIJXYZ_ DIREN
-15.988 mk	-15.380 mk	-16.432 mk

The differences between the heterogenized and homogenized WIMS_PIJXYZ_LEGENTR cases arise from the fact that in the homogenized case a dilution effect of the reactivity device occurs compared to the heterogenized case.

The differences between the WIMS_PIJXYZ_LEGENTR cases and WIMS_PIJXYZ_DIREN results can be explained by the accuracy of the calculus (the difference between the transport and diffusion formalism in strong heterogeneity treatment) and the core boundary treatment.

Also, compared with the estimated global reactivity worth for the adjuster rod system performed with the classical AECL system (~15 mk), the values obtained here is in good agreement. The difference arises from the following: the core taken in consideration in this paper is without any zone control units against with the Canadian one which had all the zone control units filled 50%.

4.2. The flux distribution

Because the fast flux is less influenced by the adjuster rod system insertion in the core, in the following we focus on the thermal flux distributions. So, in Figure 6 the thermal flux distribution in $y = 1.20$ cm plane for the reference configuration are presented.

Here it is necessary to mention that the shapes of the thermal flux obtained by both homogenized and heterogenized WIMS_PIJXYZ_LEGENTR cases for the reference configuration of the CANDU Standard core (adjuster rod system out) are similar.

In Figs. 7 and 8 there are plotted the distributions of the thermal flux in $y = 1.20$ cm plane for the perturbed CANDU Standard core (adjuster rod system in) obtained by the heterogenized WIMS_PIJXYZ_LEGENTR case and homogenized WIMS_PIJXYZ_LEGENTR case respectively.

These figures represent a proof that the development of such a calculation system like WIMS_PIJXYZ_LEGENTR is very important in highlighting the effect of the reactivity/control devices insertion in the CANDU reactor core.

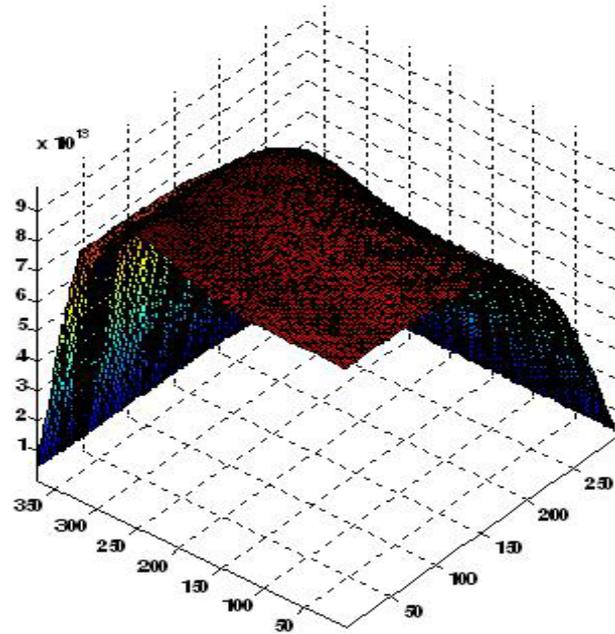


Fig. 6 – The thermal flux in the $y = 1.2$ cm plane for reference CANDU Standard core obtained by the WIMS_PIJXYZ_LEGENTR calculation system.

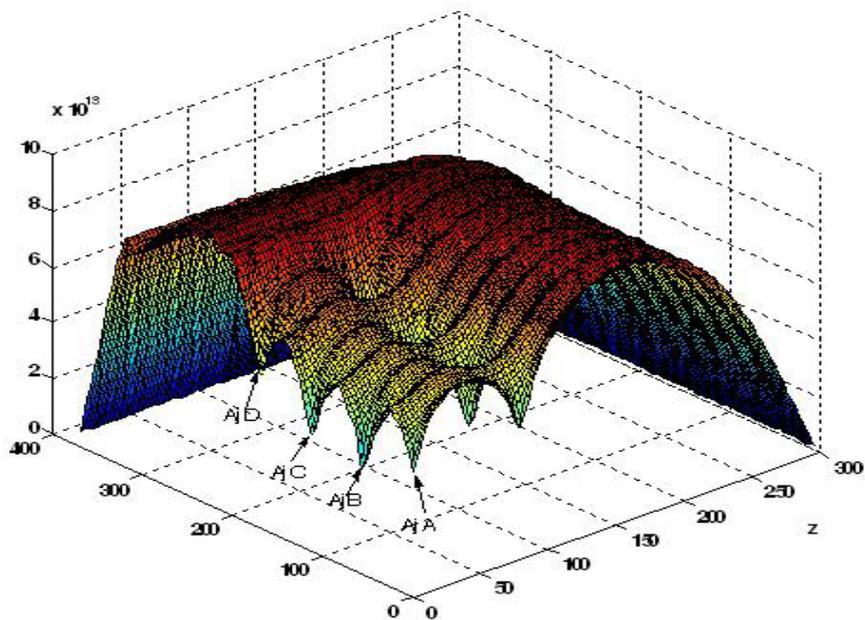


Fig. 7 – The thermal flux in the $y = 1.2$ cm plane for perturbed CANDU Standard core obtained by the heterogenized WIMS_PIJXYZ_LEGENTR system.

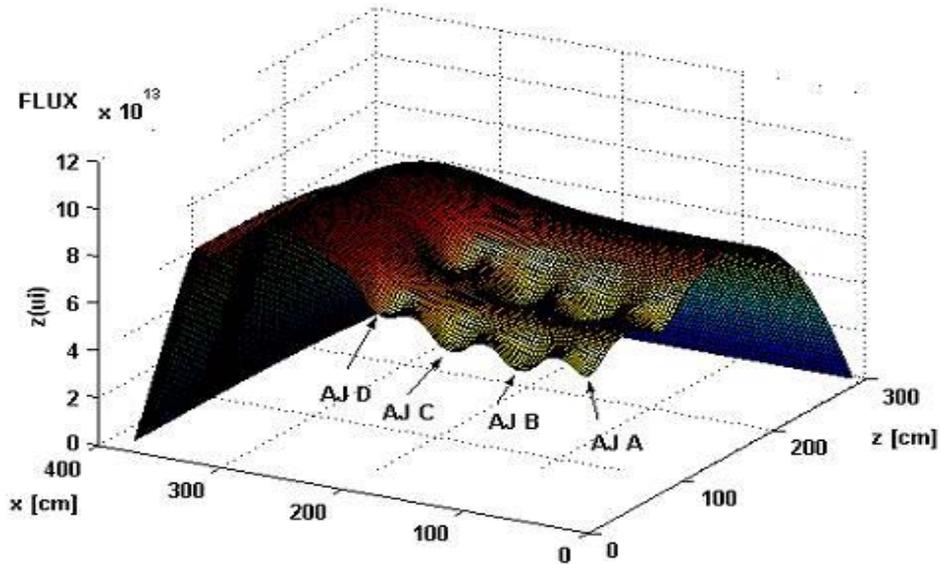


Fig. 8 – The thermal flux in the $y = 1.2$ cm plane for perturbed CANDU Standard core obtained by the homogenized WIMS_PIJXYZ_LEGENTR system.

In order to have an image of the homogenized WIMS_PIJXYZ_LEGENTR flux distribution compared with the similar obtained by WIMS_PIJXYZ_DIREN in the Figures 9 and 10 respectively there are presented the shapes of the thermal flux for the reference and perturbed configuration plotted in the central plane along the radial-horizontal direction.

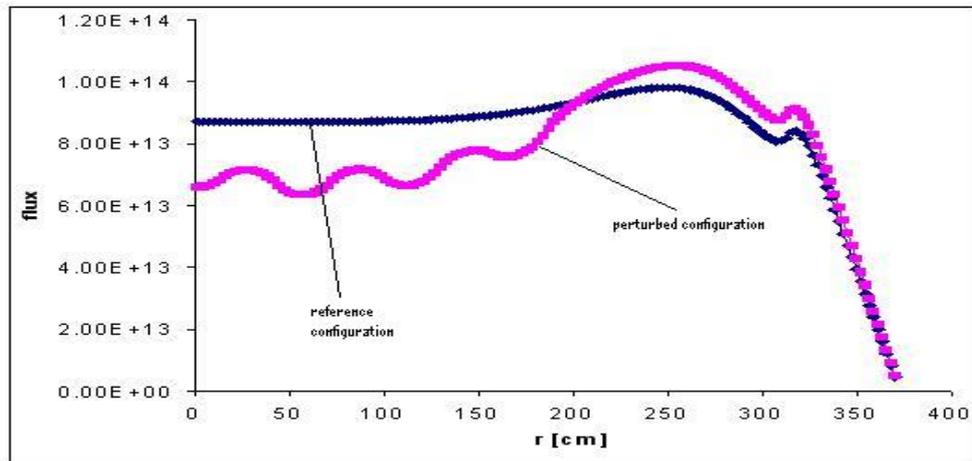


Fig. 9 – The thermal flux in the central plane radial-horizontal direction for reference and perturbed CANDU Standard core obtained by the homogenized WIMS_PIJXYZ_LEGENTR system.

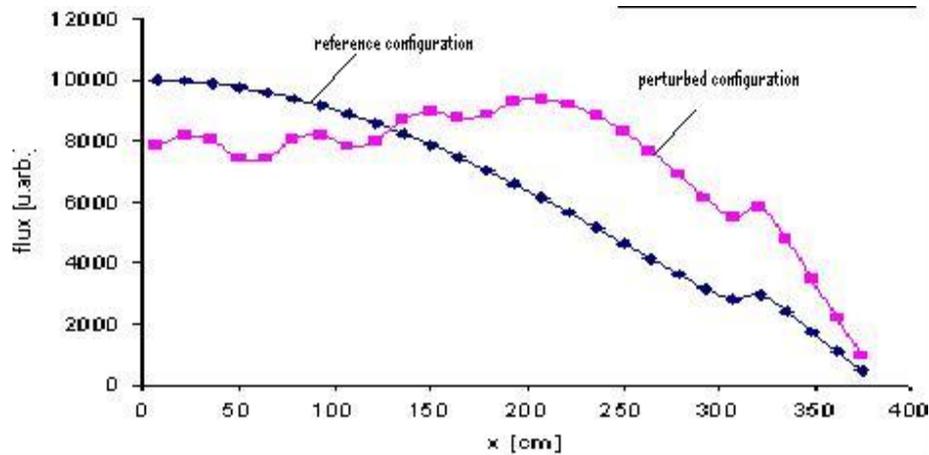


Fig. 10 – The thermal flux in the central plane radial-horizontal direction for reference and perturbed CANDU Standard core obtained by the homogenized WIMS_PIJXYZ_DIREN system.

Because the values of thermal flux are expressed in different ways (in n/cm^2s in WIMS_PIJXYZ_LEGENTR system and in arbitrary units in WIMS_PIJXYZ_DIREN) the shapes are quite different. The differences arise from the different treatment for the boundary conditions and the reflector region as well. So, in WIMS_PIJXYZ_LEGENTR system it is used the vacuum condition and in WIMS_PIJXYZ_DIREN the fluxes are vanished at the extrapolated distance.

5. CONCLUSIONS

The WIMS_PIJXYZ_LEGENTR system is a multigroup neutronic calculation system which is based only on transport codes (WIMS, PIJXYZ and LEGENTR). For this reason we can say that it is a coherent and consistent methodology which can be used successfully for estimating the global neutronic parameters specially for the CANDU reactor core. This system can with accuracy solve the strong heterogeneities that appear because of the perpendicular insertion of the reactivity/control devices on the fuel channels. It provides an precise and realistic modeling of the CANDU both supercell and core types.

The improvement the performances of this calculation system will be continued mainly in order to perform a global-local system for the fine local neutronic calculation in CANDU cores.

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