Study of the End Flux Peaking for the CANDU Fuel Bundle Types by Transport Methods

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ABSTRACT

The region separating the CANDU fuel in two adjoining bundles in a channel is called the “end region”. The end of the last pellet in the fuel stack adjacent to the end region is called the “fuel end”. In the end region of the bundle the thermal neutron flux is higher than at the axial mid-point, because the end region of the bundle is made up of very low neutron absorption material: coolant and Zircaloy-4.

For accurate evaluation of fuel performance, it is important to have capability to calculate the three dimensional spatial flux distributions in the fuel bundle, including the end region.

The work reported here had two objectives. First, calculation of the flux distributions (axial and radial) and the end flux peaking factors for some CANDU fuel bundles. Second objective is a comparative analysis of the obtained results.

The CANDU fuel bundles considered in this paper are NU_37 (Natural Uranium, 37 elements) and SEU_43 (Slightly Enriched Uranium, 43 elements, with 1.1 wt% enrichment).

For realization of the proposed objectives, a methodology based on WIMS, PIJXYZ and LEGENTR codes is used in this paper. WIMS is a standard lattice-cell code, based on transport theory and it is used for producing fuel cell multigroup macroscopic cross sections. For obtaining the flux distribution in CANDU fuel bundles it is used PIJXYZ and LEGENTR respectively codes. These codes are consistent with WIMS lattice-cell calculations and allow a good geometrical representation of the CANDU bundle in three dimensions. PIJXYZ is a 3D integral transport code using the first collision probability method and it has been developed for CANDU cell geometry. LEGENTR is a 3D $S_8$ transport code based on projectors technique and can be used for 3D cell and 3D core calculations.

1 INTRODUCTION

For an accurate evaluation of the CANDU fuel performance it is important to have the capability to calculate the three dimensional spatial flux distributions in the fuel bundle, including the end region. The “end region” is called the region separating the fuel in two adjoining bundles in a channel, [1]. In this work it is considered as the last 0.8 cm at each end of a bundle and is made up of Zircaloy-4 which is a very low neutron absorption material. This very low neutron absorption leads to a higher thermal flux in this region, effect known as "end-flux-peaking".
The objective of this paper is to underline the end flux peaking for some CANDU fuel bundles.

For an evaluation of the end flux peaking it is necessary to calculate the spatial distributions (radial and axial) of the thermal flux and the end flux peaking factors in the CANDU bundles. We take into consideration two types of CANDU bundles: NU_37 (Natural Uranium, 37 elements) and SEU_43 (Slightly Enriched Uranium, 43 elements, with 1.1wt% enrichment). Both fuels are considered fresh and at nominal power.

The methodology developed for this purpose consists in the usage of WIMS [2], PIJXYZ [3] and LEGENTR [4] codes. WIMS is a standard lattice-cell code, based on the transport theory and it is used for producing fuel cell multigroup macroscopic cross sections. For obtaining the 3D flux distributions in CANDU fuel bundles are used PIJXYZ and respectively LEGENTR codes, which are consistent with WIMS lattice-cell calculations and allow a proper geometrical representation of the CANDU bundle in three dimensions.

2 CALCULATION METHODOLOGY AND GEOMETRIC MODEL

The end flux peaking factors are defined in [1] as:

\[ P_{i}^{\text{flux}} = \frac{\Phi_{i}^{\text{end}}}{\Phi_{i}^{\text{mid-plane}}} \]  

(1)

Where:

\[ P_{i}^{\text{flux}} \] = End-flux-peaking factor in element ring \( i \) (i=1,2,3,4)

\[ \Phi_{i}^{\text{end}} \] = Fuel-end thermal flux in element ring \( I \) (I=1,2,3,4), cm\(^{-2}\)s\(^{-1}\)

\[ \Phi_{i}^{\text{mid-plane}} \] = Local thermal flux in element ring \( I \) (I=1,2,3,4) at the bundle mid-plane, cm\(^{-2}\)s\(^{-1}\)

The first step in our calculations is producing the fuel bundle cell multigroup macroscopic cross sections with 2D transport code WIMS-D4 with a 69-group ENDF/B-V library. The WIMS models of considered CANDU cells are presented in Fig.1 and Fig.2.

Fig.1 CANDU NU_37 FUEL LATTICE

Fig.2 CANDU SEU_43 FUEL LATTICE
As shown in the above figures the fuel lattices are basically the same, except the number and the dimensions of the fuel elements and the enrichment of the fuel. In the NU_37 fuel bundle there are 37 identically fuel elements and the fuel is UO$_2$, while in the SEU_43 fuel bundle there are 43 fuel elements of two sizes and the fuel is UO$_2$ with a 1.1% enrichment in U$^{235}$.

The options in the WIMS calculations are: Cell type= cluster; NG (number of energy groups in the main transport routine)=18; SEQUENCE=2 (solution of main transport equation by the collision probability method PERSEUS).

The WIMS calculations have the goal to obtain 2 and 7-group macroscopic cross sections for the homogenized materials: center fuel+sheat, inner fuel+sheat, intermediate fuel+sheat, outer fuel+sheat, structure, D$_2$O coolant, D$_2$O moderator and end material. These cross sections are used in the input of the 3D calculations made with PIJXYZ and LEGENTR.

The second step is the 3D neutron transport calculations. We perform these calculations with PIJXYZ and in parallel with LEGENTR codes.

PIJXYZ is a 3D integral transport code based on first collision probabilities method. It has been developed for CANDU cell analysis, where the reactivity devices are inserted perpendicular to the fuel channels and is similar to SHETAN code [5]. Thus, for a suitable geometrical representation, a mixed rectangular-cylindrical coordinate system is used. Because of memory and execution time requirements the code uses a combination of classical collision probabilities method (CP) and interface currents method (IC). This combined method is named “block method” (BM) and 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.

For boundary conditions PIJXYZ uses vacuum, reflective and fixed in-current distributions.

Here, the PIJXYZ calculations were made on 7 groups of energy and were applied isotropic reflective boundary conditions.

With PIJXYZ there were obtained the flux distributions in the considered supercells collapsed to 2 groups (fast and thermal) and were calculated the end flux peaking factors. For a good description of the fuel cylinder, especially in the end fuel, it is chosen fine mesh spacing (both axial and radial).

The LEGENTR program solves the transport multigroup $S_N$ equation in Cartesian X-Y-Z geometry, using the projectors method, [5]. Through the projection of the transport equation the associated transition matrix for each cell of the phase space is obtained. For large zones with strongly heterogeneous materials the space grid used could not be sufficient for keeping the calculation accuracy. For each elementary cell of the phase space a fine grid is used. The associated cellular automata is obtained by the synthesis of the responses of assemble sub-cells.

Here, with LEGENTR code there are performed the calculations of flux distributions on 2 energy groups and the end-flux-peaking factors. The boundary conditions used are reflective. Fine mesh spacing (axial and radial) is used for fuel description.
The 3D geometric models for the CANDU supercell including end region for PIJXYZ and LEGENTR codes are presented in Fig.3 and Fig.4 respectively.
The geometrical model for the 3D CANDU supercell used both in PIJXYZ and LEGENTR calculations is of dimensions 0.5LP*0.5LP*1.BL, (where LP=lattice pitch and BL=bundle length). The difference between the models in the two codes consists in the modelling of the fuel: cylindrical in PIJXYZ and rectangular in LEGENTR. It is made up equivalence (in volume and surface) for modelling the fuel in rectangular.

An X-Z layout of CANDU supercell model both for PIJXYZ and LEGENTR with a detailed end region is showed in Fig. 5.

3 RESULTS AND DISCUSSIONS

3.1 End-Flux-Peaking Factors

In Table 1 the values of end-flux-peaking factors calculated with the two transport codes PIJXYZ and LEGENTR are listed. The comparison showed good results, the values obtained with LEGENTR are higher than the value obtained with PIJXYZ with maximum 2.99%. Because the codes use the same fuel bundle cell multigroup macroscopic cross sections (from WIMS calculations), the differences are the result of both the calculation methods and the coordinates used for fuel modelling (cylindrical in PIJXYZ and rectangular in LEGENTR). At the same time our results agree with the results presented in [1], where the calculations of end-flux-peaking factors were performed with WIMS and DRAGON codes.

Thus it is observed that for SEU_43 fuel the end-fuel-peaking factors are higher than for NU_37 because of the enrichment of the fuel.
Table 1. Calculated End-Flux-Peaking Factors for NU-37 and SEU_43 Fresh Fuels at Nominal Power

<table>
<thead>
<tr>
<th>Fuel Ring</th>
<th>End-Flux-Peaking Factors in NU_37 PIJXYZ</th>
<th>End-Flux-Peaking Factors in SEU_43 LEGENTR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center</td>
<td>1.2634</td>
<td>1.3418 (+1.99)</td>
</tr>
<tr>
<td>Inner</td>
<td>1.2321</td>
<td>1.2922 (+2.27)</td>
</tr>
<tr>
<td>Intermediate</td>
<td>1.1787</td>
<td>1.2099 (+2.07)</td>
</tr>
<tr>
<td>Outer</td>
<td>1.1041</td>
<td>1.1194 (+2.09)</td>
</tr>
</tbody>
</table>

Note: Number in parentheses refers to percentage LEGENTR difference compared with PIJXYZ.

3.2 Distributions of Axial Thermal Flux in CANDU Fuel Bundles

The flux distributions in the considered CANDU fuel bundles are also calculated. For the goal of illustrating the end-flux-peaking we present the fine axial thermal flux distributions in the fuel obtained both with PIJXYZ and LEGENTR codes. The values are normalized values of fluxes.

In Fig. 6 and 7 the axial thermal flux profile in the fuel rings of the NU_37 fuel bundle obtained with PIJXYZ and LEGENTR respectively are plotted.

![Axial Thermal Flux Profile in NU_37 Fuel- PIJXYZ](image1)

Fig. 6 Distributions of Axial Thermal Flux in CANDU NU_37 Fuel Bundle Obtained with PIJXYZ

![Axial Thermal Flux Profile in NU_37 Fuel- LEGENTR](image2)

Fig. 7 Distributions of Axial Thermal Flux in CANDU NU_37 Fuel Bundle Obtained with LEGENTR
In the next figures (8 and 9), the axial thermal flux profiles in the fuel rings of the NU_37 fuel bundle obtained with PIJXYZ and LEGENTR respectively are shown:

![Axial Thermal Flux Profile in SEU_43 Fuel Bundle - PIJXYZ](image)

**Fig. 8** Distributions of Axial Thermal Flux in CANDU SEU_43 Fuel Bundle Obtained with PIJXYZ

![Axial Thermal Flux Profile in SEU_43 Fuel Bundle - LEGENTR](image)

**Fig. 9** Distributions of Axial Thermal Flux in CANDU SEU_43 Fuel Bundle Obtained with LEGENTR

In Table 2 the procentual increase for thermal flux in end region relative at middle region in considered fuels calculated with PIJXYZ and LEGENTR codes are presented.

<table>
<thead>
<tr>
<th>Fuel Ring</th>
<th>Procentual Increases in NU_37 (%)</th>
<th>Procentual Increases in SEU_43 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PIJXYZ</td>
<td>LEGENTR</td>
</tr>
<tr>
<td>Center</td>
<td>2.63</td>
<td>2.88</td>
</tr>
<tr>
<td>Inner</td>
<td>2.32</td>
<td>2.59</td>
</tr>
<tr>
<td>Intermediate</td>
<td>1.79</td>
<td>2.02</td>
</tr>
<tr>
<td>Outer</td>
<td>1.04</td>
<td>1.26</td>
</tr>
</tbody>
</table>

Table 2. Procentual Increase for Thermal Flux in End Region Relative at Middle Region in NU-37 and SEU_43 Fresh Fuel Rings

Proceedings of the International Conference “Nuclear Energy for New Europe 2005”
4 CONCLUSIONS

Both PIJXYZ and LEGENTR end-region models and calculation methods emphasize the effect of end-flux-peaking. The results obtained with these codes are similar and in good agreement with the calculations performed with DRAGON, [1]. We consider that work should continue on the calculation of the end-power-peaking factors and the power distributions in the CANDU fuel bundles.

REFERENCES


