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THE IMPACT OF THE RADIAL REFLECTOR ON THE 8-GROUP CELL-AVERAGED CROSS-SECTIONS FOR THE SCWR 62-ELEMENT LATTICE CELL

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Abstract

A single lattice cell calculation (assuming an infinite lattice) has historically been used to establish the few energy-group nuclear data required for full core simulations with deterministic codes (except for the Advanced CANDU Reactor [10]). Even though this approximation is accurate enough in the center of the core, since the flux on all cell boundaries is uniform, it turns out to be relatively inaccurate on the edge due to the presence of the reflector. This paper presents the impact of the radial reflector on the 8-group cell-averaged cross-sections of the SCWR 62-element lattice cell. For this purpose, multicell calculations have been carried out with the DRAGON code and compared to the infinite lattice simulation to determine the changes of neutronic properties due to the radial reflector. The results show that cells in contact with the reflector are quite impacted and a minimum of two fuel cell types should be added to the infinite lattice simulation to take into account the environment on the edge of the core.

Introduction

Today's core physics analysis is typically divided into two steps due to the complexity of nuclear reactor cores. The first step consists of simulating the lattice cell with the real geometry and a fine mesh (usually in 2D even though 3D calculation may be required [1, 2]) and using nuclear data in either continuous of multi-energy group format. The transport equation is then solved to determine the detailed flux and reaction distribution inside the cell. The boundary conditions for the cell typically assume an infinite lattice in all directions such that the cell boundaries are treated as reflective. Based on these simulations the neutronic interactions of this cell are homogenized over the whole cell and condensed into a smaller number of energy groups (with a minimum of two groups, but as many as eight groups for fuels such as those used in fast reactor cores). The second step simulates the full-core geometry using the diffusion approximation, but the lattice cells are now represented as a homogeneous medium with the neutronic properties generated in prior lattice simulations. The diffusion equation can now be solved to find, for instance, the power distribution.

Historically, a single lattice cell calculation (infinite lattice) was used to develop homogenized cross sections for the entire core. As a result, the effect of the environment was not taken into account and calculation errors were introduced. Therefore, several studies have been carried out to improve lattice cell calculations [3]**.**

It is important to recognize the tradeoff between accuracy, numerical complexity and calculation time. To generate all the required data for the full-core calculation, one has to keep in mind that the total time for lattice cell calculation will be the product of the simulation time for one burnup step multiplied by the number of burnup steps (around 50). This simulation will have to be done for several axial meshes (for example, 14 for the proposed SCWR design) multiplied by the number of fuel cell types (to be determined in this study). As a result, it will be very important to find a compromise between:

- The lattice cell simulation time (depends on the number of fuel cell types and the simulation time for each fuel cell type: infinite lattice/multicells).

- The accuracy in the full-core simulation [9].

The focus of this study is to assess the accuracy of differing multicell models, in particular in modelling fuel near the reflector, and to recommend the minimum number of multicell type that must be considered.

In this study, the impact of the radial reflector on the 8-group cell-averaged cross-sections has been investigated for the Super-Critical Water Reactor (SCWR) 62-element lattice cell. Using the DRAGON code [4], many multicell configurations have been investigated to estimate the cross-section discrepancies between the infinite lattice and multicell simulations. The goal here is to determine the number of fuel cell types required for the full-core calculation to be sufficiently accurate without significantly increasing the lattice cell calculation time.

1. Description of the problem

1.1. 62-element lattice cell geometry

The 62-element lattice cell [5] has a 25 cm pitch. At its center, there is a flow tube where the coolant (light water) goes downwards and turns around at the bottom to go upwards between the 62 fuel pins. These pins are surrounded by an inner liner, an insulator, an outer liner, a pressure tube and finally the moderator (heavy water) as depicted in Figure 1.

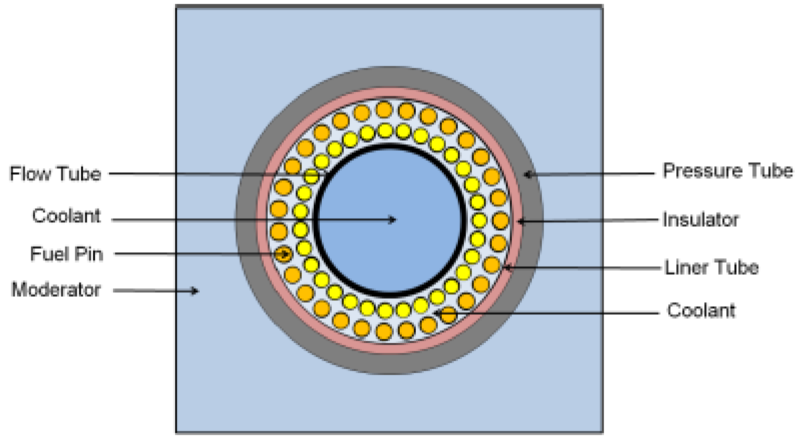

Figure 1 – SCWR 62-element lattice cell [5]

An optimized spatial meshing has been determined for the main flux calculation by generating successively finer meshes and observing the resultant predictions. Convergence is assumed to be sufficient when all 8-group cell-averaged cross-sections have less than 0.5% discrepancy compared to a very fine mesh calculated beforehand (approximately 200 meshes). All the simulations presented below have been performed using this meshing.

Table 1 – Fuel cell meshing

	Downward coolant	Center tube	Fuel pin	Cladding	Upward coolant
Meshes	25	1	10	2	25
	Inner liner	Insulator	Outer liner	Pressure tube	Moderator
Meshes	1	3	1	5	10

1.2 Temperatures and densities along the channel

The Super-Critical Water Reactor (SCWR) operates above the critical point of water (373.95°C, 22.064MPa). Because of that, the coolant undergoes an important temperature and density variation as shown in Figure 2. Consequently, axial meshing is required to take into account the temperature and density changes along the channels on the flux, as well as on the burnup characteristics for that fuel. A number of 14 meshes have been chosen following the results of Harrison and Marleau [6]**.** However, the size of the meshes has been slightly modified for two reasons:

- 500cm divided by 14 does not give an exact value, which is not convenient.
- The size of the meshes was adapted to follow more closely the coolant density changes, since it is one of the most important parameters in the simulation.

Figure 2 shows the discretization of the temperature and the density of the coolant along the channel. The temperature of all the other materials have been discretized as well but are not shown here because their impact is not as significant as the coolant's.

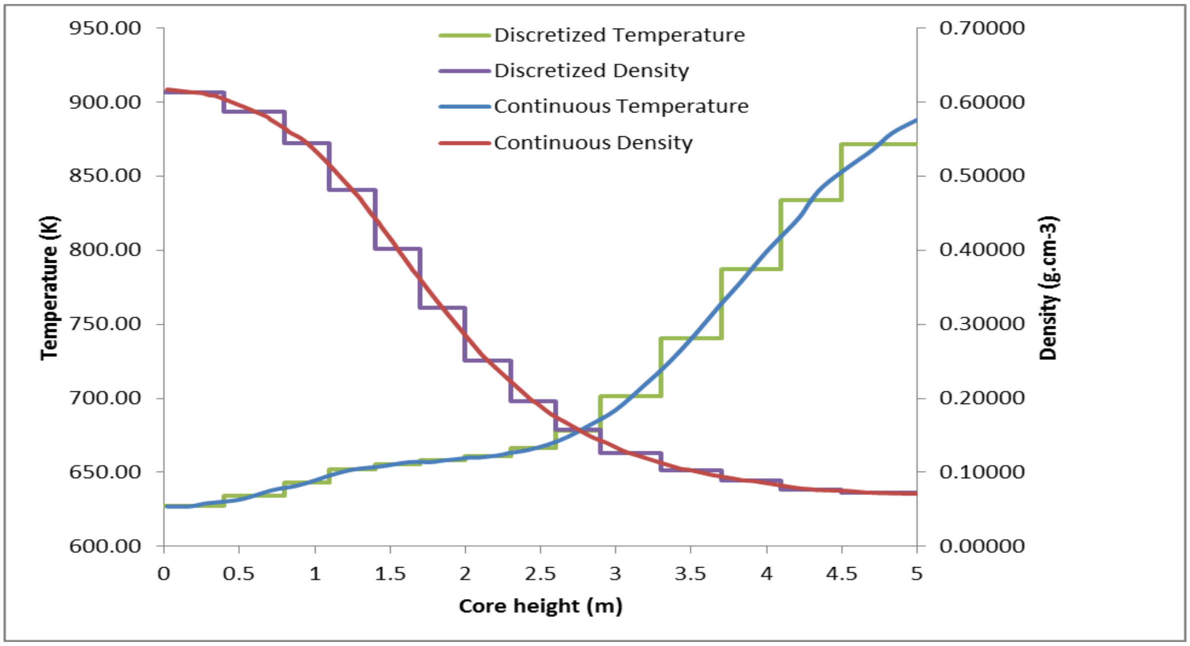

Figure 2 – Discretization of the coolant Temperature and Density along a channel

The DRAGON code was used in this study because of its flexibility and robustness. DRAGON [4] is a deterministic code developed by École Polytechnique de Montréal. After calling a library, describing the geometry and doing a self-shielding calculation, the transport equation is solved for a unit cell in 2D or 3D. Then, it generates the homogenized and/or condensed cross-sections, fluxes and reaction rates which are going to be used as inputs for the full-core simulation with the diffusion code DONJON [7].

2. Methodology of the study

To observe the impact of the radial reflector on fuel cells, several configurations have been investigated. Two distinct types of boundary cells can be defined near the reflector:

- *side cells*: they are the cells the least impacted by the reflector, as only one side of the closest fuel cell touches a reflector cell as shown in Figure 4.

- *corner cells*: the cell in the corner has two sides in contact with reflector cells. The geometry depicted in Figure 5 is the most heterogeneous corner in the full-core geometry [5] compared to the infinite lattice.

Treatment of each of these cells is discussed separately below.

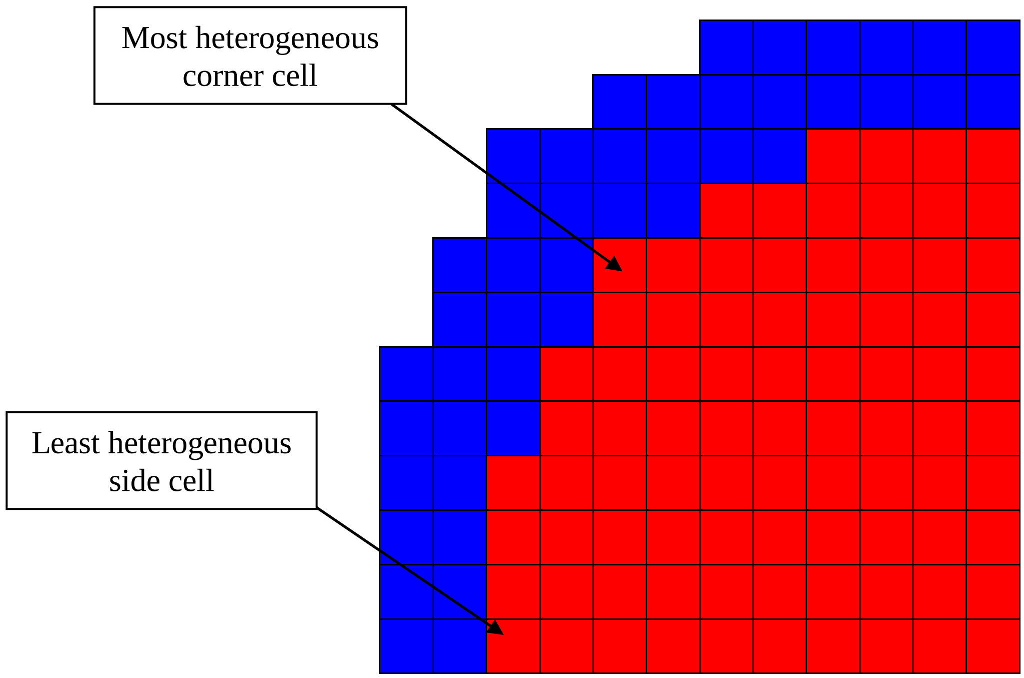

Figure 3 – Quarter of the SCWR core (red: fuel cells / blue: reflector cells)

2.1 Side cells

In Figure 4, possible geometrical configurations of the side cells in DRAGON are explicitly shown. Here the main difference in simulating side cell properties is the number of fuel channel represented within the simulation.

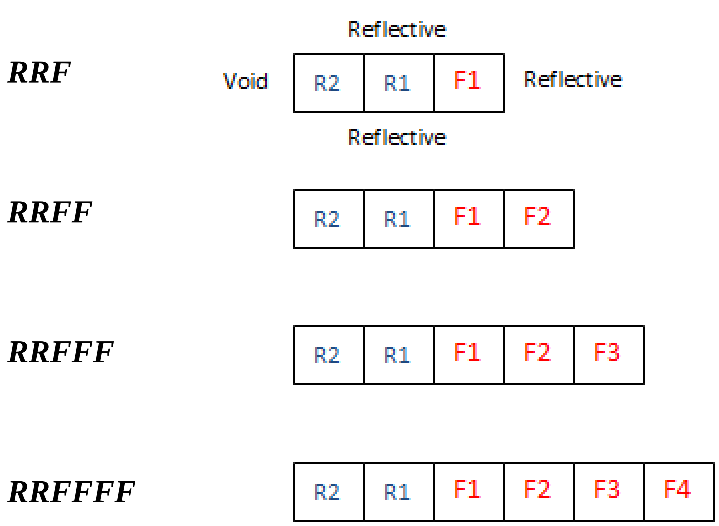

Figure 4 – Side cells configurations

First, the impact of the reflector is studied for the closest fuel cell: F1. The methodology applied to get the discrepancies between F1 and the infinite lattice is described below:

1. DRAGON simulations are performed with successively increased number of fuel channels (see Figure 4 above) and the cross-section changes in cell F1 are evaluated. When every single 8-group cell-averaged cross-section has less than 1% difference, the neutronic properties are considered converged with respect to side cell modelling.

2. To observe the impact of the radial reflector on F1, cross-sections are compared to those for the infinite lattice for each of the 8 groups.

The reflector study described above is repeated for three separate axial locations:
- Mesh 1: bottom of the core (highest coolant density)
- Mesh 6: coolant mid-density value
- Mesh 14: top of the core (lowest coolant density)

Finally, the entire procedure above is repeated for cell F2, where the effect of multicell modelling on the fuel assembly next to the side cell is examined.

2.2 Corner cells

Options for modelling geometrical configurations of the corner cell are depicted in Figure 5.

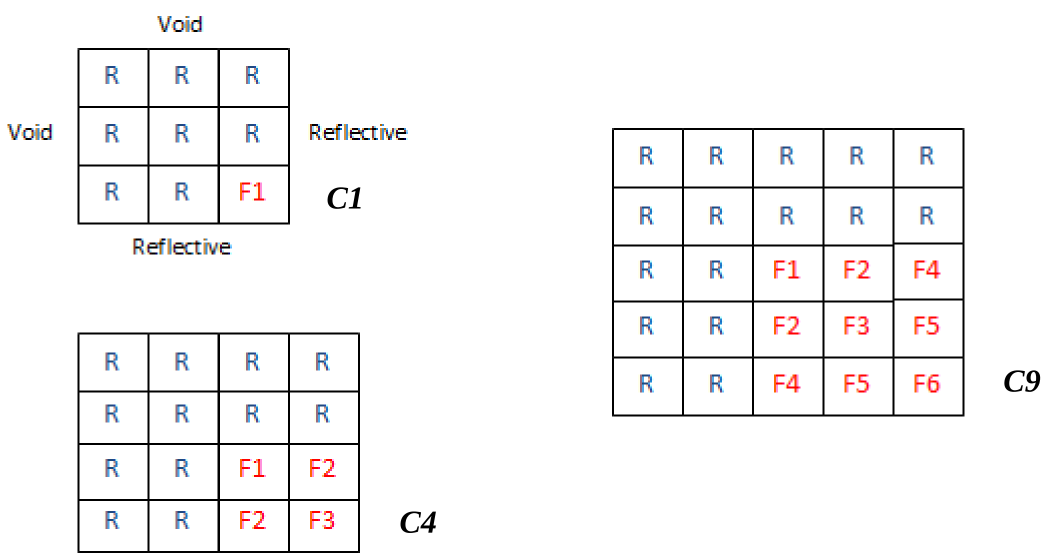

Figure 5 – Corner cells configurations C1/C4/C9

The same methodology for studying side cell effects is applied to C1, C4 and C9. Cells F1, F2 and F4 are studied and all the results are presented below.

3. Results

For simplicity's sake, the results are shown only for one core height each time (where the highest discrepancies are observed). The formula used to get the discrepancy with the infinite lattice is:

$$Discrepancy\ (\%) = \frac{\Sigma_{Multicell} - \Sigma_{Infinite\ lattice}}{\Sigma_{Infinite\ lattice}} \times 100$$

Cut-off values for the eight groups are [8]:

Energy group	Lower energy cut-off (eV)
1	2.2313×10^{6}
2	8.2085×10^{5}
3	9.1188×10^{3}
4	1.3007×10^{2}
5	3.9279×10^{0}
6	6.2506×10^{0}
7	1.4572×10^{0}
8	0.0000×10^{0}

Reference cross-sections for the 8 groups for the infinite lattice are presented below (Table 2).

Table 2 – Reference cross-sections for 8 energy groups for the infinite lattice

Energy group	1	2	3	4	5	6	7	8
Total XS	1.53E-01	2.32E-01	3.86E-01	4.54E-01	4.50E-01	4.62E-01	5.78E-01	6.38E-01
Fission XS	1.08E-03	8.31E-04	2.76E-04	9.27E-04	4.84E-03	1.73E-03	1.81E-02	1.01E-02
Capture XS	6.95E-04	3.58E-04	5.94E-04	3.57E-03	5.68E-03	1.66E-02	1.55E-02	9.86E-03
Scattering XS								
From \ To	1	2	3	4	5	6	7	8
1	8.01E-02	4.27E-02	2.84E-02	6.54E-05	2.37E-06	4.32E-08	9.51E-09	5.07E-10
2	2.30E-08	1.40E-01	9.10E-02	2.62E-04	3.21E-06	6.80E-08	7.26E-12	7.51E-13
3	-	-	3.46E-01	3.97E-02	2.19E-04	6.87E-06	1.21E-06	2.96E-07
4	-	-	-	3.99E-01	5.00E-02	7.74E-04	1.36E-04	3.93E-05
5	-	-	-	-	3.70E-01	6.20E-02	5.71E-03	1.36E-03
6	-	-	-	-	2.19E-04	3.30E-01	1.02E-01	1.19E-02
7	-	-	-	-	-	1.82E-03	3.91E-01	1.51E-01
8	-	-	-	-	-	1.68E-06	3.31E-02	5.85E-01

3.1 Step 1: Finding the optimized geometry

On Figure 6 below, one can observe the convergence of two cross-sections (fission cross-section for group 7 and 8) while successively increasing the number of fuel cells. When the convergence criterion of 3% was verified for each cross-section in every group, the corresponding geometry was chosen.

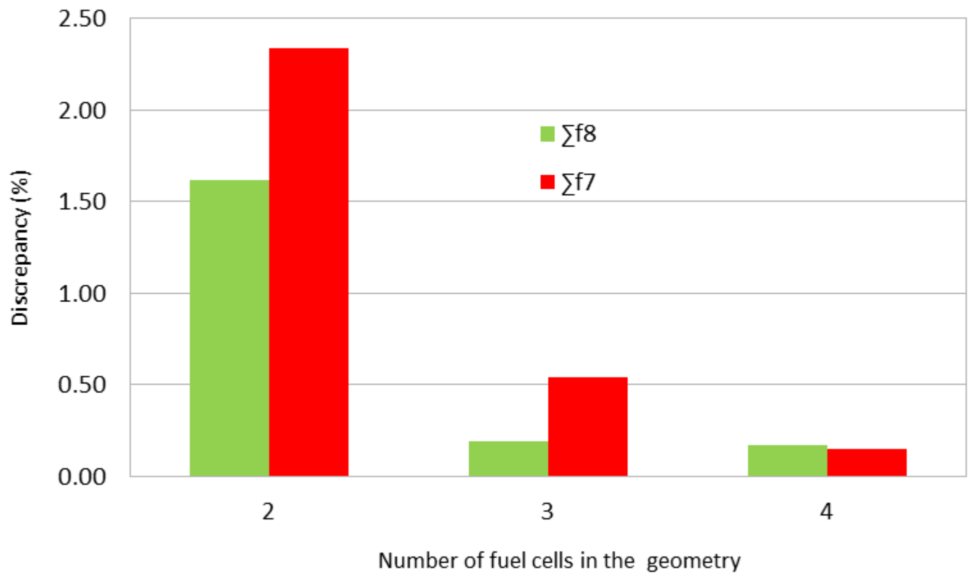

Figure 6 – Cross-section convergence while successively increasing the number of fuel cell

3.2 Step 2: Observing the impact of the reflector

3.2.1 Side cells

Table 3 presents the discrepancies for the total, absorption and fission cross-section as well as the scattering matrix between F1 in the geometry RRFF and the infinite lattice at the bottom of the core. Table 4 shows these discrepancies for F2 in the geometry RRFFF and the infinite lattice at the same axial location.

Table 3 – Discrepancies (%) between F1 (RRFF) and the IL (bottom of the core)

Energy group	1	2	3	4	5	6	7	8
Total XS	-0.5	-0.5	0.5	1.8	1.6	1.5	0.2	-5.3
Fission XS	4.7	3.9	6.5	4.8	3.9	3.1	1.2	-9.1
Capture XS	3.8	3.8	3.8	3.6	4.0	3.1	0.8	-9.4
Scattering XS								
From \ To	1	2	3	4	5	6	7	8
1	-0.5	0.8	-0.5	3.6	3.0	4.3	4.4	4.4
2	3.7	-0.1	-1.4	3.2	3.1	3.3	2.6	3.1
3	-	-	0.8	-1.9	4.1	4.1	4.1	3.7
4	-	-	-	1.7	2.0	7.1	7.1	7.1
5	-	-	-	-	1.3	2.1	5.6	6.7
6	-	-	-	-	2.4	1.1	2.0	3.9
7	-	-	-	-	-	-6.1	-1.0	3.2
8	-	-	-	-	-	-20.3	-15.4	-4.6

Table 4 – Discrepancies (%) between F2 (RRFFF) and the IL (bottom of the core)

Energy group	1	2	3	4	5	6	7	8
Total XS	-0.1	-0.1	0.1	0.7	0.8	0.9	0.9	-1.3
Fission XS	0.6	0.5	1.5	1.7	2.1	2.1	1.5	-3.0
Capture XS	0.6	0.5	0.9	1.3	2.2	2.0	1.4	-2.9
Scattering XS								
From \ To	1	2	3	4	5	6	7	8
1	-0.1	-0.2	-0.1	0.6	0.8	0.6	0.5	0.5
2	0.5	0.0	-0.3	0.5	0.5	0.5	0.7	0.6
3	-	-	0.2	-0.8	1.0	1.0	1.0	0.9
4	-	-	-	0.7	0.3	2.5	2.5	2.5
5	-	-	-	-	0.7	0.8	2.6	3.3
6	-	-	-	-	1.8	0.7	1.1	2.3
7	-	-	-	-	-	-0.8	0.4	2.2
8	-	-	-	-	-	-5.2	-4.2	-1.1

Based on these results, cell F1 is impacted by the reflector and it is obvious that the infinite lattice model has limited applicability for these periphery channels. The most thermal group, which is the most impacted, has around 9% discrepancy for the fission and absorption cross-section. Moreover, the discrepancies for the up-scattering from group 8 to groups 6 and 7 are the most noticeable (respectively -20.3% and -15.4%) even though they probably won't have a great impact during the full-core diffusion calculation. Overall, every group in cell F1 is affected by the reflector, and hence at least one side cell should be considered as a distinct fuel type in addition the infinite lattice cell.

To a large extent, cell F2 is less sensitive to the reflector since it is one full lattice further from the reflector interface. While there is a trend towards increasing discrepancy with decreasing energy, the effect is still small with respect to fission and capture cross sections. As shown in Table 4, the discrepancy does not exceed three percent except for the up-scattering cross-section from group 8 to groups 6 and 7 (respectively -5.2% and -4.2%). Based on this result no separate multicell fuel type is required for the side cells that are more than one lattice pitch from the reflector interface.

3.2.2 Corner cells

Table 5 displays the discrepancies between F1 in the geometry C4 and the infinite lattice at the bottom of the core.

Table 5 – Discrepancies (%) between F1(C4) and the IL (bottom of the core)

Energy group	1	2	3	4	5	6	7	8
Total XS	-1.1	-0.9	1.1	3.7	3.4	3.2	1.1	-7.4
Fission XS	9.5	7.8	13.1	10.2	8.5	7.0	3.0	-13.2
Capture XS	7.7	7.6	7.8	7.7	8.6	7.0	2.3	-13.5
Scattering XS								
From \ To	1	2	3	4	5	6	7	8
1	-1.1	-1.7	-1.1	7.5	6.1	8.8	9.0	9.0
2	7.5	0.2	-2.7	6.5	6.4	6.7	5.2	6.2
3	-	-	1.6	-3.4	8.5	8.5	8.4	7.7
4	-	-	-	3.6	4.4	15.1	15.1	15.1
5	-	-	-	-	2.9	4.5	12.0	14.5
6	-	-	-	-	5.4	2.5	4.4	8.6
7	-	-	-	-	-	-9.7	-1.1	6.5
8	-	-	-	-	-	-28.5	-21.7	-6.4

Table 6 – Discrepancies (%) between F2(C4) and the IL (bottom of the core)

Energy group	1	2	3	4	5	6	7	8
Total XS	0.65	0.55	-0.67	-2.70	-2.79	-2.93	-2.21	4.79
Fission XS	-5.33	-4.45	-8.25	-7.35	-7.28	-6.71	-4.08	9.18
Capture XS	-4.37	-4.35	-4.86	-5.61	-7.47	-6.68	-3.69	9.29
Scattering XS								
From \ To	1	2	3	4	5	6	7	8
1	0.62	0.96	0.64	-4.35	-3.55	-4.97	-5.05	-5.05
2	-4.30	-0.09	1.61	-3.83	-3.77	-3.90	-3.11	-3.63
3	-	-	-1.05	2.72	-5.32	-5.34	-5.28	-4.83
4	-	-	-	-2.66	-2.55	-10.78	-10.78	-10.78
5	-	-	-	-	-2.44	-3.29	-9.70	-11.87
6	-	-	-	-	-5.46	-2.31	-3.73	-7.58
7	-	-	-	-	-	4.87	-0.48	-6.41
8	-	-	-	-	-	18.61	14.57	4.09

As seen in these tables there is a strong deviation from the infinite lattice cross sections for the corner cells. Similar conclusions were made at the two upper core elevations.

3.3 Interpretation of the results

Larger discrepancies have been found for the corner cell compared to the side cell. Therefore, two fuel cell types should be added to the infinite lattice one:

- Side cells: one side in contact with the reflector
- Corner cells: two sides in contact with the reflector

The discrepancies found for the two simulations performed (side and corner cell) are the extreme bounds for all cells in contact with a reflector cell. In fact, for a cell touching the reflector, the side cell simulation represents the least heterogeneous geometry contrary to the corner simulation which represents the most heterogeneous configuration.

However, looking at the second most impacted cell in the core (which is F2 in the corner cell geometry C4), the discrepancies observed with the infinite lattice are quite similar to those of the side cell F1 (see Table 6 above). Therefore, instead of doing two separate simulations for the side and corner cells, only the corner cell simulation can be carried out with the geometry C4. In the end, cell-averaged cross-sections can be extracted from the cell F1 for the corner cells and from F2 for the side cells.

Once these two sets of cross-sections will be incorporated to the full-core calculation, the lower fission cross-section value in the eighth group will result in a higher thermal flux in these cells as observed in figure 6 below.

3.4 Flux spectrum effects

Figure 7 depicts the flux spectrum shift between F1 in the RRFF geometry, F1 in the C4 geometry and the infinite lattice.

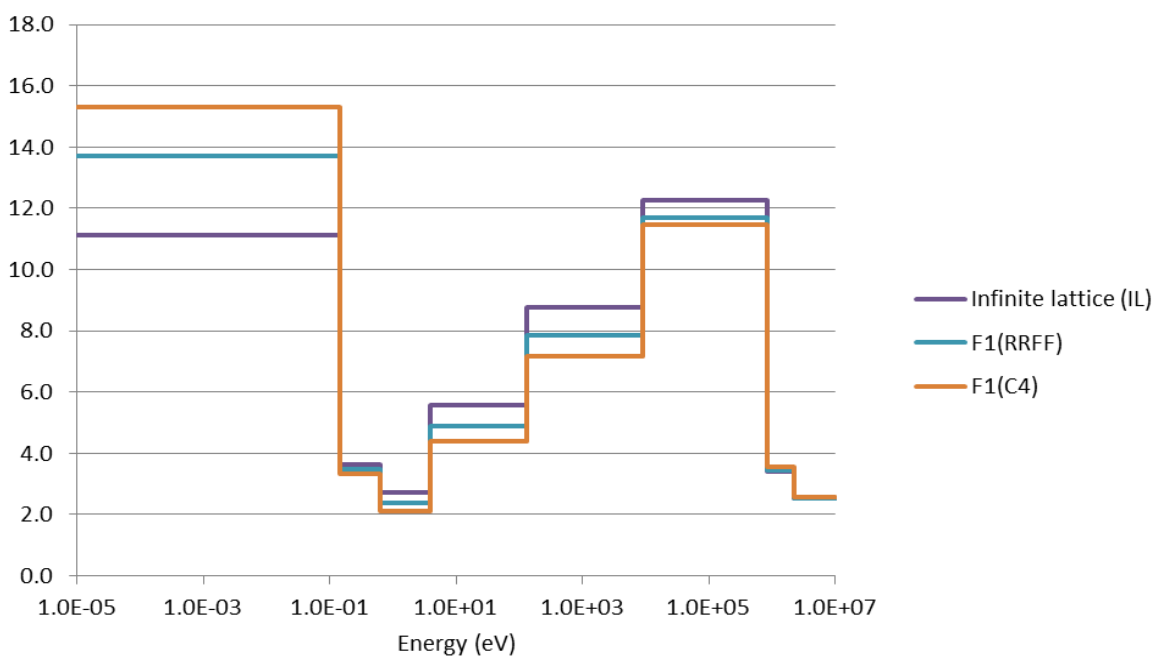

Figure 7 – Flux spectrum shift between F1(RRFF), F1(C4) and the IL (bottom of the core / normalized to 100 neutrons)

Because of the reflector cells, which principally slow down neutrons, the flux spectrum is shifted towards thermal energies. In Figure 7, one can observe the increase of flux in the eighth group for the side cell (F1(RRFF)) and corner cell (F1(C4)).

3.4 Reflector cells

Besides the cell-averaged cross-sections for fuel cells, neutronic properties have been calculated for the reflector cells. Full-core calculations typically employ only one set of cross-sections for every reflector cell. Table 7 shows that neutronic properties differ quite significantly between the cell R1 and R2 in the side cell simulation.

Table 7 – Discrepancies (%) between R2 and R1 for the side cell geometry

Energy group	1	2	3	4	5	6	7	8
Total XS	3.0	1.6	-0.2	0.0	0.0	0.0	-1.4	-0.2
Capture XS	85.2	-1.3	1.6	-11.5	-5.9	-1.6	-7.6	-0.7
Scattering XS								
From \ To	1	2	3	4	5	6	7	8
1	-3.7	9.6	11.5	-22.3	6.9	-	-	-
2	-	-1.1	4.4	4.5	4.3	11.2	-	-
3	-	-	2.1	-13.8	-10.9	-10.9	-10.7	-12.5
4	-	-	-	3.7	-25.8	-19.6	-19.6	-19.6
5	-	-	-	-	2.8	-15.0	-19.9	-14.0
6	-	-	-	-	10.9	1.6	-4.6	-5.3
7	-	-	-	-	-	76.8	8.9	-22.9
8	-	-	-	-	-	3.2	4.3	-0.3

Even though discrepancies are relatively large for many cross-sections for R2, it does not imply that the full-core simulation will be significantly impacted if cross-sections from R1 are used for R2. In fact, firstly, the flux in these cells is almost only thermal and neutrons are mostly scattering. Hence the most important cross-sections are the scattering cross-sections for the most thermal groups (7 and 8). Secondly, the flux in R2 is lower than in R1, and hence their effect on the global power distribution in a diffusion calculation may be very small.

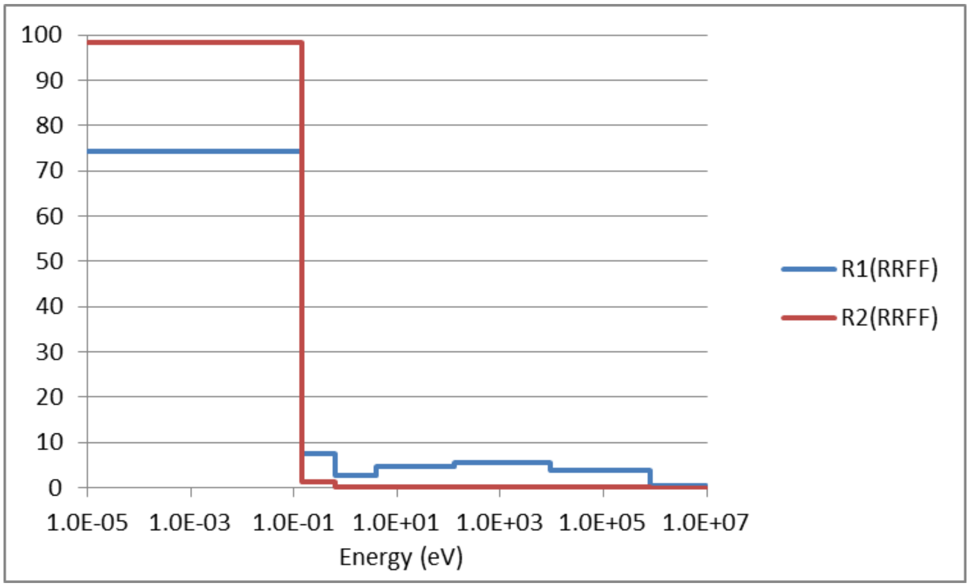

Figure 8 – Comparison between the flux spectrum in R1 and R2 (normalized to 100 neutrons)

A full-core simulation would need to be carried out to determine if the use of R1 cross-sections for R2 is a good approximation.

4. Conclusion

This study allowed us to investigate the impact of the radial reflector on the 8-group cell-averaged cross-sections for the SCWR 62-element lattice cell. Results show that the impact of the radial reflector is not negligible at the lattice level. In fact, a minimum of two fuel cell types should be added to the infinite lattice type in order to account for the heterogeneity brought by the radial reflector. Moreover, these two fuel cell types only require one more simulation at the lattice level. However, a full-core diffusion calculation would be needed to demonstrate if the discrepancies observed at the lattice level have a significant impact or not. Finally, the cell-averaged cross-sections for the reflector are quite different if the cell is in contact with the fuel or if the cell is in contact with the void. A full-core calculation would need to be carried out to determine if two reflector cell types are needed.

5. Future work

All these calculation have been carried out for a fresh fuel lattice cell. Therefore, a study should be performed to observe how discrepancies evolve with burnup. Afterwards, a full-core simulation should be developed in order to implement all these changes. Hence, a comparison between the single lattice cell core and a core with the two new fuel cell types could be done. A calculation with one or two reflector cell types could be carried out as well.

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