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SPATIAL MESHING EFFECT AND REFLECTOR TREATMENT IN PWR CORE MODELING

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ABSTRACT

The reflector treatment is an important issue in modeling a LWR core by using deterministic codes. A sensitivity analysis has been performed in order to evaluate the influence of two parameters on the multiplication factor and on the relative radial power distribution: 1) the reflector thickness to be used in cell calculation for cross section generation; 2) the size of the reflector mesh which can be defined during core calculation after the homogenization. By using the deterministic code WIMS, a 14x14 rods fuel assembly type and a 2 loop PWR Westinghouse reactor core have been modeled. After cross sections have been generated for fuel assemblies and reflector materials, 3D-core calculations are performed by the SNAP module. The spatial meshing effect has been investigated not just for the reflector geometry surrounding the core but also for the fuel assembly geometry by changing the meshing scheme adopted for the entire core in the SNAP module. The results are shown for two different meshing schemes: a scheme of a mesh per fuel assembly and 5x5 meshes per fuel assembly. As a result of the analysis, it can be noted that the reflector thickness and the meshing scheme for performing core calculations have an important influence on the parameters selected for the analysis itself, particularly on the multiplication factor and the relative radial power value.

Key Words: PWR core, Reflector, Mesh size, Multiplication factor, Relative radial power distribution

1. INTRODUCTION

Reflectors play a fundamental role on the neutron balance and on the neutron flux distribution in the core. In fact, the dimension of a core can be reduced if some of the leaking neutrons are reflected back into the core; moreover the reflector has a benefit on the neutron flux distribution by making it more uniform [1]. In modeling a LWR core by using a deterministic code, the extraction of data for the reflector is an important topic and in literature it is not easy to find papers relative to this issue. After reflector cross sections are generated, the problem is to obtain effective reflector data which can be used in core calculations. Since normally a 1D or a 2D reflector calculation is performed, it has been noted that reflector data are influenced by the meshing scheme adopted in setting the grid for the transport calculation module and by the thickness of the reflector considered. Therefore, a sensitivity analysis has been performed by using the deterministic code WIMS9A. A typical PWR 2-loop Westinghouse core has been

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modeled (i.e., BEZNAU, DOEL-1 and DOEL-2) with a 14x14 fuel assembly type [2]. A description of the reference geometry has been presented in the next paragraph.

WIMS9A is the modern development of WIMSD which was supplied by the WIMS development team to the NEA and the RSICC databanks in the mid 1960's [3]. Since, it is still one of the most requested software and one of the standard tools for reactor analysts worldwide. WIMS9A has specific service modules for reflector data calculation; a description of the reflector model has been given in the next section.

In order to investigate the effect of the reflector treatment on the multiplication factor and on the relative fuel assembly wise power distribution, two parameters have been taken into account: 1) the reflector thickness; 2) the reflector spatial meshing scheme adopted in the SNAP code, which is the 3D-diffusion module for core calculations. A sorting of the results obtained is described in section 3.

The spatial meshing effect has been also analyzed, since if it is clear that the increment of the meshes' number per fuel assembly gives more confident results, it is not so obvious to quantify the effect itself.

2. CORE MODEL

This section comprises a brief description of the fuel assembly and the core geometry. The model is based on the typical 2-loop Westinghouse PWR. It is also shown how the reactor core has been modeled with WIMS and which modules have been used for performing the calculations.

2.1. Fuel Assembly Specification

The fuel assembly (FA) is a square array of 14 x14, i.e. 196 possible positions, of which 179 are fuel rods and the remaining 17 are guide tubes. A guide tube (GT) is normally empty or it can house a group of burnable absorber rods (BAR, 8 or 12 rods) or a control rod group (16 rods). The central GT may be occupied by instrumentation. Fuel rods cladding is Zircalloy-4 and GT material is SS-304. Inconel-718 is the material of the spacer grids, in a total number of 7 with five to be considered in the active length. In fact, for the neutronic calculation just 5 spacers grid are spread in the volume of a FA. Fuel assembly burn-up calculations are performed as presented in Figure 1 for the 11 different types of FAs.

The flow chart shows that, after number densities are written in the module HEAD for reading the microscopic cross sections from the library and for the resonance treatment, multi-cell collision probabilities are calculated with the PERSEUS module. Cross section and collision probabilities are used in the PIP module for the calculation of the infinite multiplication factor and the fluxes in each material. After this step, and in order to accelerate the calculation procedure, the energy groups are condensed from 172 to 6. Therefore, a 6 group transport equation is solved in each region of the FA with the module CACTUS. The BURNUP module is used for burn-up calculations for each material by specifying a power rate for a FA type. Before performing the material buckling search with the CRITIC module, a radial spatial homogenization is performed in order to reduce the number of materials relative to each fuel pin single mesh. The radial homogenization is performed with the SMEAR module. After this, a condensation from 6 to 2 groups is performed and in order to have an assembly wise homogenization, an additional calculation is performed by means of the SMEAR module . At the end, for each fuel assembly, the necessary two groups' parameters are obtained and 3D core calculations can be performed with the SNAP module which can solve the multi-group neutron diffusion equations using finite difference methods in several co-ordinates.

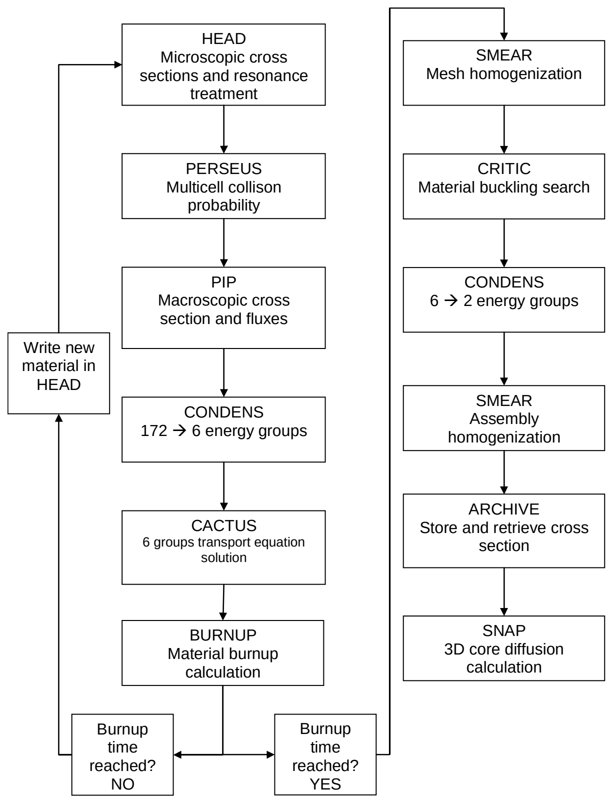

Figure 1. Modules used in WIMS9 for burn-up calculation

2.2. Reactor Core Description

The reactor core has an equivalent diameter of 246.01 cm and an active length of 304.8 cm. At the first loading, the core is composed of 121 fuel assemblies (FAs) arranged in three different enrichment regions, as follows:

- 1st region has 41 FAs, with 2.44% of ^{235}U;
- 2nd region has 40 FAs, with 2.78% of ^{235}U;
- 3rd region has 40 FAs, with 3.48% of ^{235}U.

The core thermal output considered is 1130 MW and the average temperature at Hot Full Power (HFP) is 573.15 K. The reactor power control and the safety shutdown are performed with control and safety rod banks housed in specific FAs. There are 29 rod cluster control assemblies:

8 groups for safety (SR) and 17 full length control banks (CB1 and CB2) and 4 partial length control banks (PL) for the axial flux oscillation control. Figure 2 shows a sketch of the core.

Reactivity effects are controlled with boric acid and with burnable absorber rods (BARs) housed in several FAs and symmetrically arranged in the core, as follows:

- 1st region: 4 FAs housing 8 BARs, 8 FAs housing 12 BARs;
- 2nd region: 8 FAs housing 8 BARs, 20 FAs housing 12 BARs;
- 3rd region: 8 FAs housing 12 BARs.

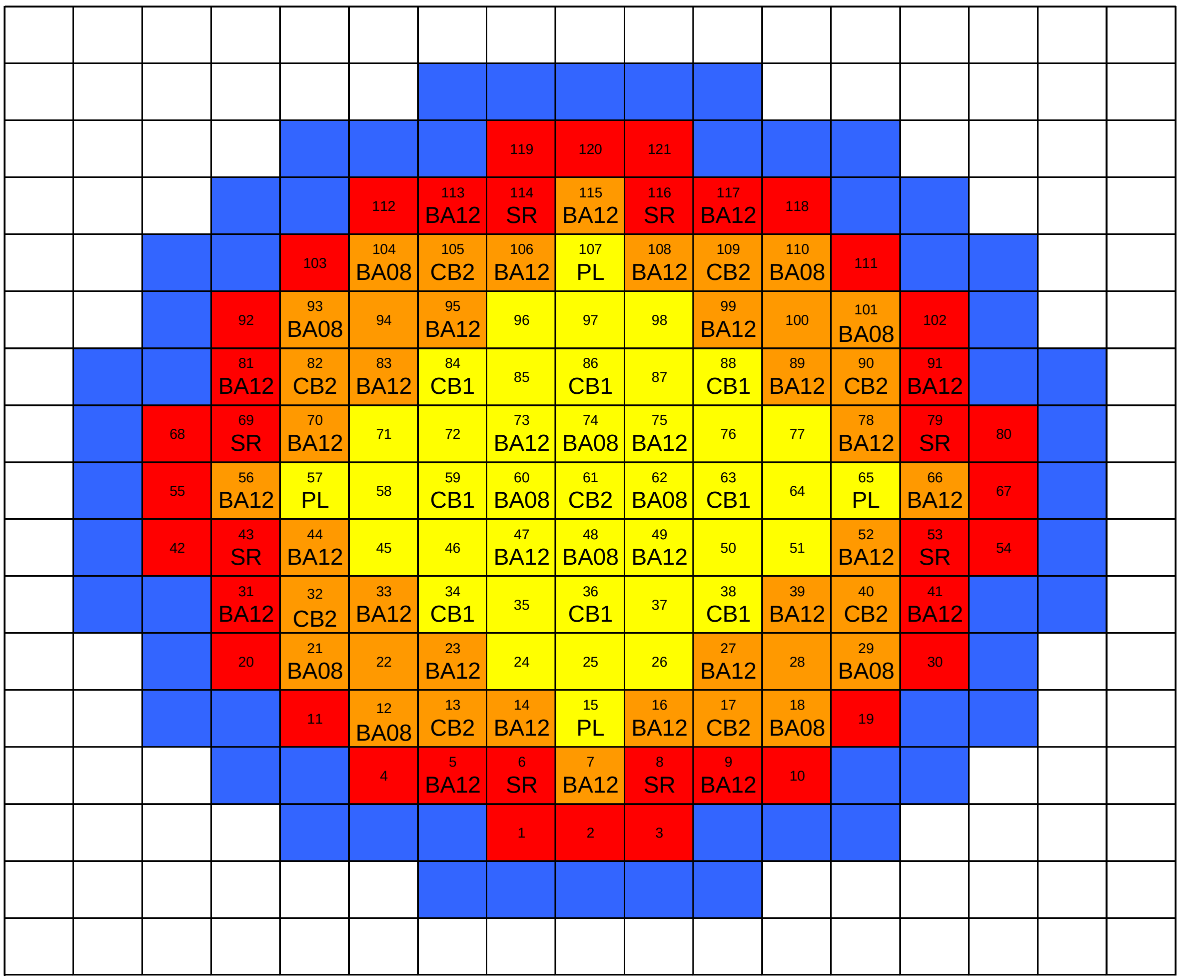

Figure 2. 2D Core Map

Table I gives the legend for the Figure 2 above.

Table I. Legend of symbols in Figure 2

(red)	=	fuel 3.48%
(orange)	=	fuel 2.78%
(yellow)	=	fuel 2.44%
(blue)	=	Reflector
	=	Black absorber
N	=	N =1,…, 121 fuel assembly number
BA12	=	12 Burnable Absorber
BA08	=	8 Burnable Absorber
CB1	=	Control Bank1
CB2	=	Control Bank2
SR	=	Safety Rods
PL	=	Partial Length Rods

2.3. Reflector Description

The reactor core is surrounded by the baffle, the barrel, the thermal shield and finally the reactor vessel. Between each of these there is a gap of water that together with the SS constitutes the lateral reflector. The contributions of water and SS are taken into account by the volume fractions of each. Clearly, for example, if the barrel rather than the thermal shield is considered as part of the reflector calculation, different volumes for the water and the SS should be considered.

For the top reflector, fuel plenum and top nozzle are considered; for the bottom reflector, all the parts from the end plugs till the core support are considered. Top and bottom reflector are not part of the present analysis since they do not affect the radial distribution and their effect on the multiplication factor is negligible. For the reflector cross sections generation and flux calculation, the procedure represented in Figure 1 is modified in order to generate reflector data (see Figure 3). Therefore MIX and LED modules are introduced in order to replace the downscattering by absorption and for obtaining the effective data.

The purpose of the module MIX is to mix material composition and microscopic cross sections in order to form macroscopic cross sections. It has a special option, REFLECTOR, which is used for generating reflector data, in which downscattering past a given energy is replaced by absorption.

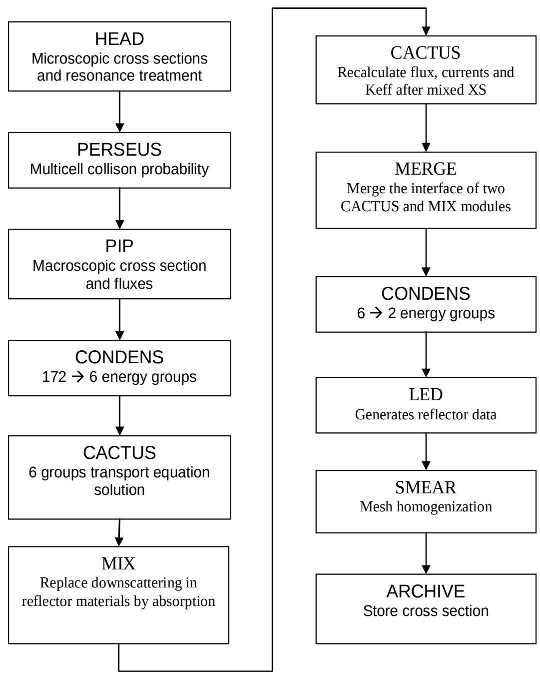

Figure 3. Modules used in WIMS9 for burn-up calculation

The purpose of the module LED is to set up a library of cross sections and nuclear data, labeled by material name. The data associated with a single material name may represent either a fuel assembly or the reactor reflector within the whole core. In order to represent the fuel, a fuel assembly or a super-cell is modeled. In order to represent the reflector, a rectangular slice containing both fuel and reflector material is used, with the core on the left hand side and the reflector on the right hand side (see Figure 4, in which the dark blue area represents the reflector on the right hand and the scheme of the FA is on the left hand). Therefore, the LED module will calculate effective reflector data. The interface read by the LED module contains two group currents from two calculations which have been combined using the MERGE module.

It should be noted that Figure 4 is simply a material map and does not show the length of the meshes; for example, the inter-fuel assembly (IFA) meshes are definitely smaller than those adopted for the fuel assembly and for the reflector material. The assembly grid shows 16 meshes in the Y direction (the first and the last mesh for the IFA water with a dimension of 0.026 cm) and 19 meshes in the X direction (the first, the 16^{th} and the 17^{th} for the IFA water with a dimension of 0.026 cm). Each mesh in the fuel region is representative of the channel in which the fuel rod or the guide tube can be inserted and the dimension is 1.412 cm. The mesh relative to the reflector materials has dimensions corresponding to the reflector thickness as shown in Table II. The reflector is a mixture of water and SS, considered as a zone adjacent to a FA. It should be clarified that the number of FAs adjacent to the reflector has not a relevant influence on the generation of effective data. It has been considered that it is sufficient for the present analysis to take into account just one FA with an enrichment of 3.48%.

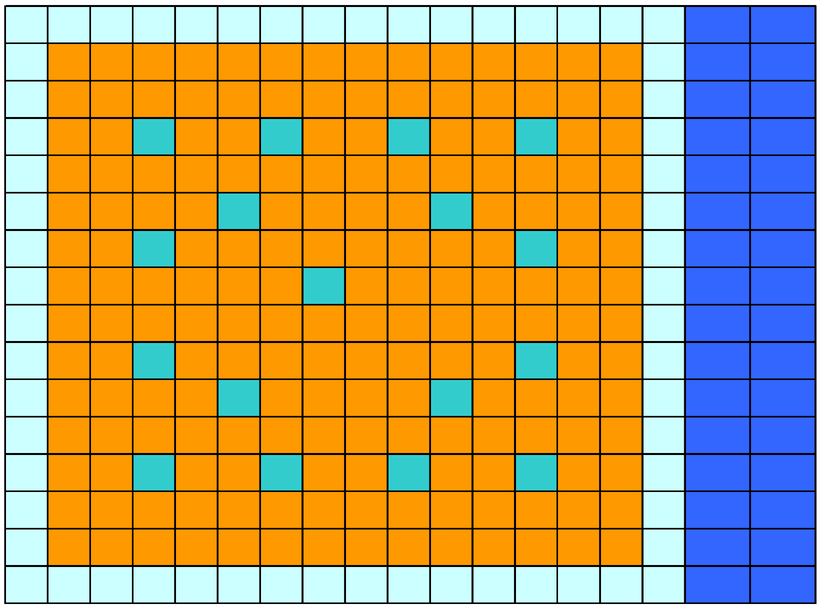

Figure 4. Material map for reflector calculation

Table II. Legend of symbols in Figure 2

	=	Fuel 3.48%
	=	Guide tubes
	=	Inter-fuel assembly water
	=	Reflector

3. REFLECTOR SENSITIVITY ANALYSIS

In this paragraph some of the results are presented that were obtained by means of a sensitivity analysis on the radial power distribution and the effective multiplication factor by changing the reflector thickness and the mesh size of the reflector considered in the SNAP module.

All the results reported in this paragraph correspond to the core at HFP and xenon and samarium equilibrium. Burn-up calculations have been performed for the model adopted and the results at 520 full power days (FPD) of irradiation are presented. The value of 520 FPD has been considered as the end-of-life (EOL) for the first core loading analysis. However, it should be mentioned that the burn-up module has not been used for the cross section calculation of the reflector materials. In fact, reflector materials are not affected by the burn-up and it is better to consider the fuel at beginning-of-life (BOL) in terms of conservative analysis.

3.1. Reflector Thickness Influence

Starting from a clean core condition at HFP, the critical condition and the Xe and Sm equilibrium are reached. An initial value for the reflector thickness of 14.22 cm was considered. The reflector meshing scheme in 2D transport equation solved by the CACTUS module comprises 2 nodes in one direction and 16 nodes in the other, corresponding to the FA adjacent meshing scheme. The reflector spatial mesh in the SNAP module is defined by one single node, and in the reflector thickness analysis the dimension of the mesh was set at 28.44 cm.

Results for the thickness influence are presented in Table III. As can be observed, by increasing the reflector thickness, which corresponds to considering different reactor zones, the K_{eff} decreases. Starting from a critical core condition, a difference of almost 600 pcm is obtained by increasing the reflector thickness. Moreover, the thickness has a relevant influence on the power distribution.

Table III. Reflector thickness effect on K_{eff}

Nodes	cm	Lateral Reflector Thickness	Vol Fr.	%	k_{eff}
thickness	19.913	lateral reflector thickness till **barrel outer radius**	coolant	58.1%	0.99780
2 nodes	9.957		steel	41.9%	
thickness	23.355	lateral reflector thickness till **thermal shield inner radius**	coolant	64.7%	0.99674
2 nodes	11.678		steel	35.3%	
thickness	32.411	lateral reflector thickness till **thermal shield outer radius**	coolant	45.1%	0.99610
2 nodes	16.205		steel	54.9%	
thickness	43.333	lateral reflector thickness till **vessel inner radius**	coolant	60.5%	0.99455
2 nodes	21.666		steel	39.5%	
thickness	59.932	lateral reflector thickness till **vessel outer radius**	coolant	41.4%	0.99372
2 nodes	29.966		steel	58.6%	

The relative radial power distributions for four of five cases reported in Table III are presented in Figures 5 and 6. From these figures, it can be easily deducted that the increase in the lateral reflector thickness results in a more peaked power distribution towards the core center as, for the vessel inner radius case, the relative power peak value moves from the 3^{rd} to the 1^{st} region.

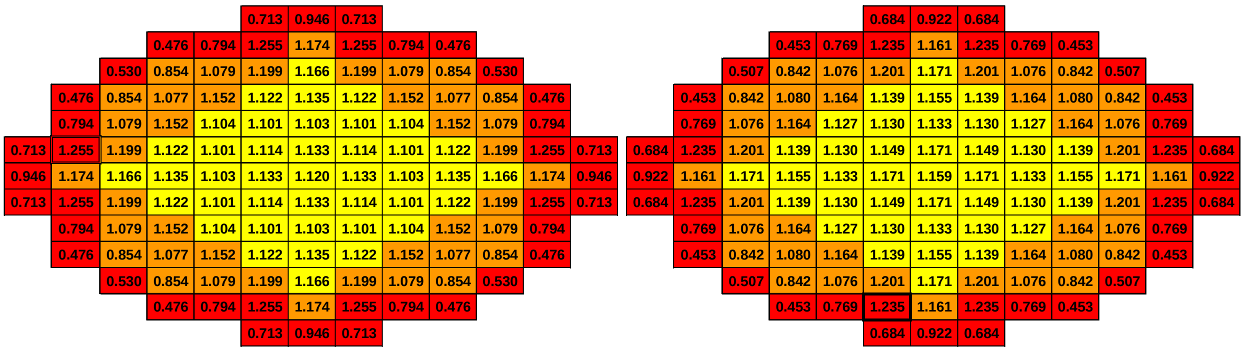

Figure 5. Relative radial power distribution for a lateral reflector thickness till the barrel outer radius (on the left) and for a lateral reflector thickness till the thermal shield inner radius (on the right)

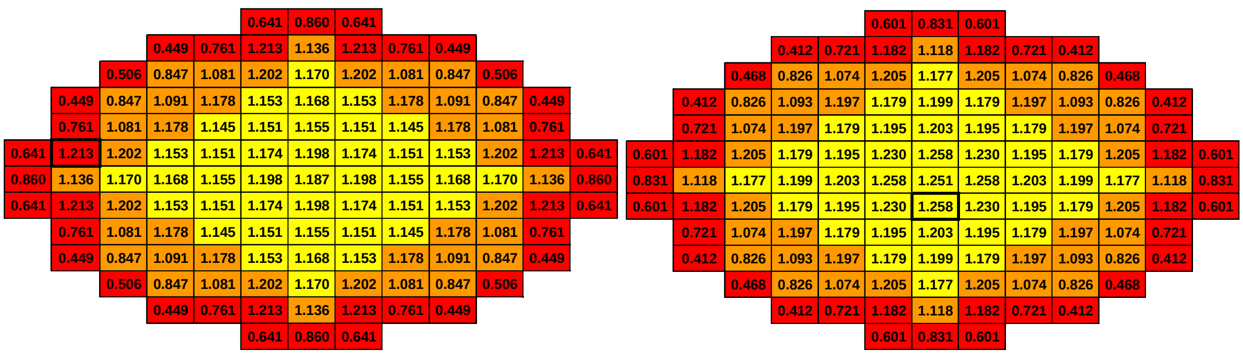

Figure 6. Relative radial power distribution for a lateral reflector thickness till the thermal shield outer radius (on the left) and for a lateral reflector thickness till the vessel inner radius (on the right)

3.2. Reflector Spatial Mesh-Size Effect

In this document just two examples are presented. In this case, the reflector thickness has been defined as the thickness corresponding to the thermal shield outer radius. Therefore, the mesh size has been changed corresponding to the reflector dimensions in the SNAP module. In Figure 7 the results for the core at critical boron condition (64 ppm) are shown. Considering the symmetry, just a quarter of the core is represented in the figure.

1.1873	1.1979	1.1548	1.1682	1.1696	1.1360	0.8598
1.1979	1.1741	1.1505	1.1525	1.2020	1.2130	0.6410
1.1548	1.1505	1.1449	1.1782	1.0811	0.7607	
1.1682	1.1525	1.1782	1.0913	0.8472	0.4492	
1.1696	1.2020	1.0811	0.8472	0.5058		
1.1360	1.2130	0.7607	0.4492			
0.8598	0.6410					

1.2703	1.2776	1.2179	1.2043	1.1591	1.0491	0.6541
*1.2776	1.2486	1.2117	1.1901	1.1995	1.1412	0.5043
1.2179	1.2117	1.1997	1.2204	1.0967	0.7464	
1.2043	1.1901	1.2204	1.1299	0.8704	0.4546	
1.1592	1.1995	1.0967	0.8704	0.5216		
1.0491	1.1412	0.7464	0.4546			
0.6541	0.5043					

Figure 7. Relative radial power distribution for a lateral reflector thickness till the thermal shield outer radius with a mesh size of 28.44 (on the left) and a mesh size of 3.964 (on the right)

Starting from a reflector dimension of 28.44 cm considered in the previous analysis, the mesh size used in the SNAP module for the reflector has been defined at 3.964 cm which is the size relative to the FA mesh scheme. The first value was set as a tentative value resulting from a preliminary analysis. As can be noted, the mesh size used for the reflector in performing the core calculations has an important influence on the relative power distribution. The relative power peak value in Figure 7 on the left is in the 3rd region – FA No. 8. The effect of reducing the mesh size results in a new power distribution (figure on the right side) with the relative peak value placed in FA No. 36 in the 1st region. The K_{eff} is less affected by the mesh size (180 pcm), as was reasonable to expect.

3.3 Spatial Meshing Effect

After homogenization, the effect of the reflector mesh size in the SNAP module causes a modification of the assembly wise radial power distribution and has no particular effect on the reactivity. However, in the SNAP code, the size of the mesh can be decreased by increasing the number of meshes per FA. The results for two different meshing schemes are presented in Table IV: one is based on one mesh per FA scheme; the other divides the cross section area of the FA in 5x5 meshes. Starting from a core in critical condition at 0 FPD, and thus without changing the content in terms of boron concentration, the 1x1 and the 5x5 meshing schemes have been compared by analyzing the influence on the multiplication factor during burn-up. Results have been extracted at several FPD of irradiation and by considering the xenon build-up concluded after 20 days.

Table IV. Meshing scheme effect on K_{eff}

FPD	20	70	180	260	320	360	520	525	527
K_{eff} 1x1	0.97147	0.96997	0.95561	0.94396	0.93526	0.92945	0.9053	0.9047	0.90433
K_{eff} 5x5	0.96272	0.96226	0.94893	0.93768	0.92915	0.92338	0.89915	0.89854	0.89818
Δ (pcm)	875	771	668	628	611	607	615	616	615

4. CONCLUSIONS

The sensitivity analysis on the reflector thickness and on the spatial mesh shows that the influence of the reflector thickness can be in the order of hundreds of pcm depending on the reactor core. The spatial mesh size has a strong influence on the radial power distribution and contributes to the multiplication factor itself. However, the reflector mesh size does not particularly affect the multiplication factor, but the spatial meshing scheme adopted in the SNAP module for core calculations does. It has an effect quantified between 900 and 600 pcm depending on the burn-up. Instead, all other calculations presented above regarding reflector treatment are based on a 5x5 meshes scheme in the SNAP module.

The analysis given in paragraph 3.1 and 3.2 shows how the core calculation can be affected by the reflector treatment influencing important parameters such as, for example, shutdown margin (SDM), and critical boron concentration.

In fact, SDM, for example, is calculated with all the CRs inserted but the highest worth reactor cluster control assembly (RCCA) totally withdrawn. The selection of the highest worth RCCA is strongly influenced by the assembly wise radial power distribution, which is affected by the reflector treatment. Regarding the calculation of the boric acid for determining the criticality of the core or the search of the critical boron concentration, the interpolation method has been used. However, if for the first core loading at EOL a conservative boron reactivity coefficient of about 7.5 pcm/ppm can be assumed, the influence of the reflector thickness on the boron concentration can result in a difference of about 54.4 ppm between the barrel outer radius case and the vessel outer radius case. This value is significant when the life of the core should be determined.

For further developments it is important to discuss how to avoid this influence and to define a unique solution for the reflector calculation. Further analyses have already been implemented and better results were obtained. These results show that improvements can be obtained in the reflector treatment by having the same number of meshes for the reflector as for the adjacent FA. These enhanced results will be presented in future.

ACKNOWLEDGMENTS

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APPENDIX A

Table V shows the abbreviations used in this document.

Table V. Glossary

BOL	Begin of Life
BAR	Burnable Absorber Rod
CB1	Control Bank 1
CB2	Control Bank 2
CR	Control Rod
EOL	End Of Life
FA	Fuel Assembly
FPD	Full Power Day
HFP	Hot Full Power
GT	Guide Tube
IFA	Inter-Fuel Assembly
PL	Partial Length control rod
RCCA	Rod Control Cluster Assembly
RPD	Relative Power Distribution
SDM	Shut Down Margin
SR	Safety Rod
SS	Stainless Steel