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DETAILED NEUTRONIC MODELLING OF THE CROCUS RESEARCH REACTOR USING APOLLO3[®] TRANSPORT CODE

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1. INTRODUCTION

The CROCUS experimental reactor, powered by Swiss Federal Institute of Technology, Lausanne is a light water moderated critical assembly with the two-zone core containing oxide and metallic uranium fuel pins. This is a reactor of a small size approximately of cylindrical shape in which the criticality conditions are reached by changing the water level. The reactor has been used for many experiments and some of these have been approved as benchmark configurations and published in the international community allowing the verification of computer codes and nuclear data [1]. Besides a constant effort by the APOLLO3[®] development group to enrich the validation base of the code with a variety of reactor configurations, a particular interest in CROCUS reactor is in the ongoing experimental program of the reactor noise measurement, which is a part of the European project in which CEA participates.

Two different approaches of the reactor noise calculations have been implemented in APOLLO3, one in the frequency domain using the transport and diffusion flux solutions in 2D and 3D homogenized geometries[2], and another in temporal domain with the flux solutions in 2D heterogeneous configurations[3]. The interpretation of the experiment will comprise the calculation of CROCUS using these two options.

The work presented here is out of the scope of reactor noise analysis and focuses on the calculation methodology of this particular reactor in a general case that will be later adapted to a given experiment. This is considered as a preliminary step having objective to analyse different possibilities to model the CROCUS reactor and to setup a comprehensive calculation scheme that gives the precise answers about the reactivity, the reaction rates and flux distributions that will allow an easy comparison with reactor measurements to be performed in foreseen campaigns.

Among many possibilities that offers the APOLLO3 as a modular code, the attention is oriented toward the selfshielding calculation options, the choice of the fully heterogeneous two-dimensional reactor model, the homogenization procedure and the three-dimensional homogenized model. Two flux solvers that have noise calculation capability are the 2D variant of the TDT, a method of characteristic (MOC) module [4] and the 2D/3D variant of the IDT, discrete ordinates code that uses homogeneous meshes. [5]

Recent CROCUS calculations[6,7] that are based on the classical approach of cross section homogenization with the three-dimensional calculations using the two-group diffusion theory may not provide satisfactory results for the detailed reaction rate distributions. The renewed scheme relies on accurate Monte Carlo calculations for the production of homogenized cross sections but still using diffusion theory. Such obtained results still show the discrepancies of

around 400 pcm in reactivity and more than 10 % in pin-wise power distribution. Increase in number of groups (up to 40), but still relying on diffusion approximation, does not provide a significant improvement.

Our classical approach is extended to the whole-reactor 2D heterogeneous transport calculations for the production of homogenized cross sections, which is expected to reduce these errors by an order of magnitude. The 2D results presented here show the discrepancies of about 100 pcm in reactivity and around 1 % in pin-wise fission rates compared to TRIPOLI-4 Monte Carlo results.[8]

2. TWO-DIMENSIONAL REACTOR MODEL

Contrarily to the power producing LWRs, the particular design of the CROCUS reactor with a non-uniform lattice and a relatively small core makes the standard two-step calculation procedure difficult to apply. On the other hand, the increased moderation due to higher water-to-fuel volume ratio, the low operating temperature and higher fuel density (metallic fuel of the outer core) require a careful spatial discretization for the flux calculation. The preliminary tests have been conducted separately for the infinite lattice configurations of the two kind of fuel together with the selfshielding options. All results shown here are based on the standard fine-structure selfshielding method. The results for oxide fuel cells show good agreement with Monte Carlo reference, which is 4 pcm difference in reactivity, while for metallic fuel this method gives a discrepancy of 130 pcm. The spatial dependent selfshielding calculations are performed on a simplified geometry (not shown in this summary) that comprises a 2D array of UO_2 and metallic fuel pin cells, water gap and reflector. Example of the MOC spatial mesh on the eightfold symmetric geometric domain is shown in Fig. 1. Table 1 shows the results of one of parametric studies involving different MOC integration parameters and different orders of scattering anisotropy. The discrepancy of the asymptotic solution is in the agreement with the error observed on the single cells calculations in which the principal source of error is the selfshielding model. One may conclude that the MOC approximation does not introduce any further bias. The pin-wise reaction rate errors are shown in Fig. 2 and 3. Maximum relative error is around 1% with the RMS of relative errors equal 0.5%.

Table 1: Errors in effective multiplication factor compared to Monte Carlo reference (in pcm) for various scattering anisotropy orders (P_n) and different MOC quadratures. (N_φ and Δr are respectively number of azimuthal angles and trajectory spacing.)

P_n order	MOC quadrature ($N_\varphi, \Delta r$ [mm])								
	16, 0.5	16, 0.25	16, 0.1	20, 0.5	20, 0.25	20, 0.1	24, 0.5	24, 0.25	24, 0.1
0	-1120	-1173	-1171	-1110	-1166	-1180	1075	-1113	-1121
1	-225	-287	-286	-223	-283	-300	-205	-257	-262
3	-94	-157	-156	-90	-152	-168	-74	-127	-132
5	-90	-152	-151	-85	-146	-163	-68	-121	-126

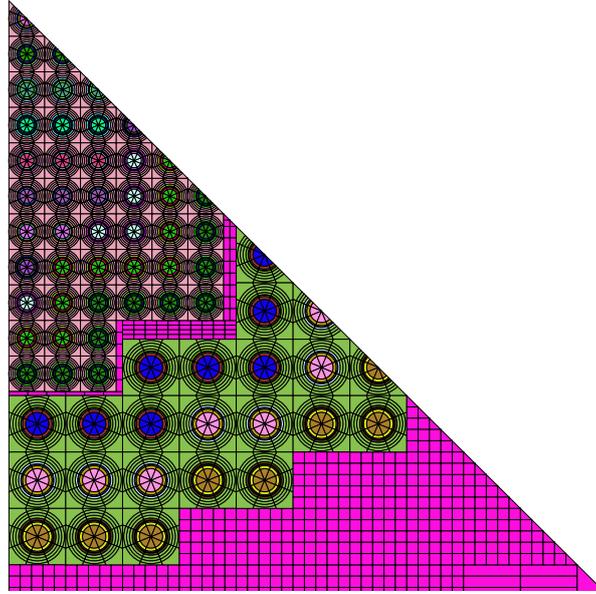


Figure 1: Example of the MOC spatial mesh in a 2D heterogeneous geometry model. The colours in fuel pins indicate different self-shielding regions adopted for this calculation. The image is truncated over the reflector zone.

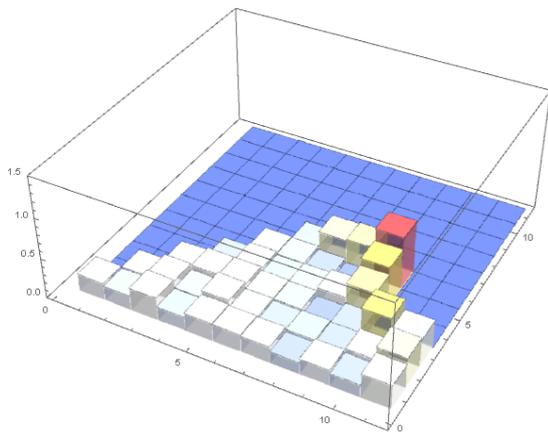


Figure 2: Fission rate relative errors in oxide fuel (in%).

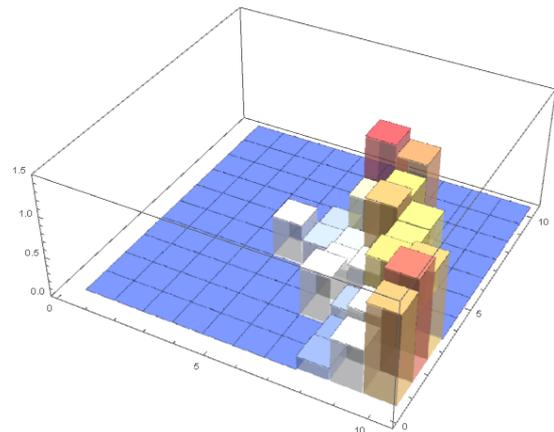


Figure 3: Fission rate relative errors in metal fuel (in%).

3. HOMOGENEOUS MODEL

In order to construct a 3D homogeneous model, pin-wise homogenization is done using the above shown 2D heterogeneous solution. Different multigroup structures have been investigated with the number of groups varying between 26 and 281. The homogeneous flux calculation uses short characteristics with the linear flux expansion. Simple flux and volume weighting produces the errors in reactivity between 300 and 400 pcm with the pin-wise rate distribution errors that reach 3 %. (The error distributions will be shown in the full paper.) The most of these discrepancies are situated in the fuel near the internal water gap and at the core-reflector interface. Indeed, strong flux gradients occur in these zones. As illustration, we show in Fig. 4 the flux distribution in the group where the flux in water reaches the highest value in the thermal energy range. The remedy to this problem is the application of the equivalence procedure

where the equivalence coefficients are sought iteratively using the fixed point iterations. Figure 5 shows the equivalence factors for different oxide and metallic fuel pin cells situated along the axis of the reactor. Significant elongation from the value of 1.0 happens in the deep thermal energy range in the whole core and the dips can be observed around the position of the lowest ^{238}U resonances. We consider such modified equivalent cross sections acceptable.

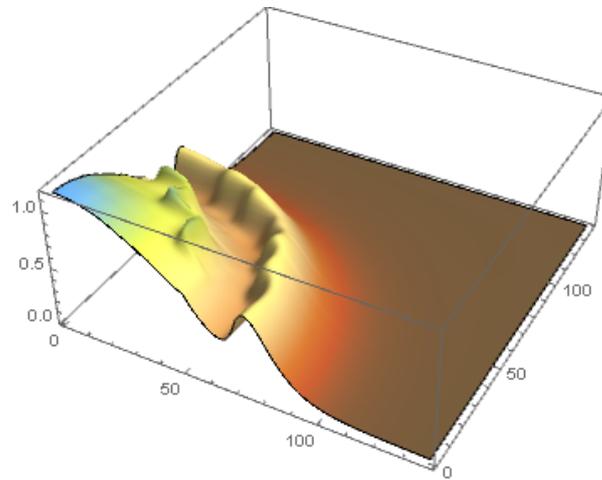


Figure 4: Thermal flux distribution at the energy of flux maximum in the water gaps and reflectors.

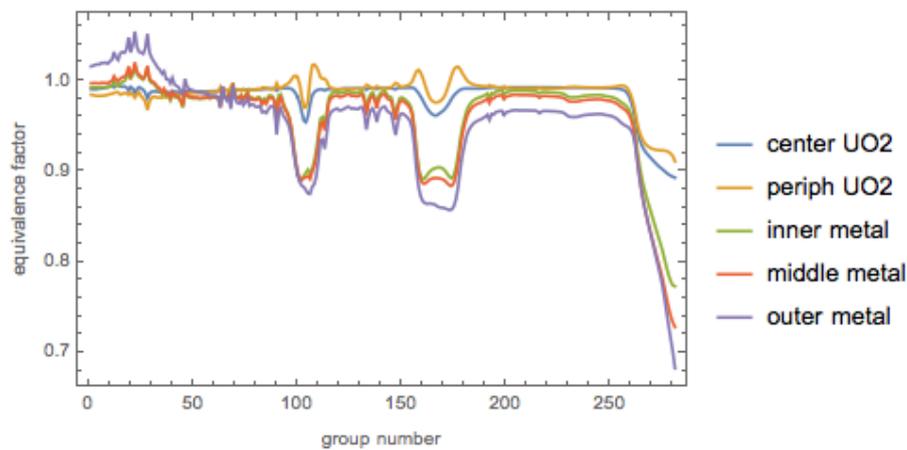


Figure 5: Multigroup equivalence factors of selected fuel pins along the x -axis in a 281-group calculation.

4. CONCLUSIONS

This work represents the preliminary activities in order to set an efficient calculation scheme for the CROCUS reactor that will be used for the interpretation of measurements. Heterogeneous 2D model gives satisfactory results, although further improvements are possible, especially in the selfshielding applied to the metallic fuel, e.g. the subgroup method instead of the fine structure one. The detailed results will be presented in the full paper, as well as 3D results compared with the Monte Carlo reference.

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