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Impact of *3D* modeling and homogenization of control rods on reactivity in CFV-type SFR cores

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INTRODUCTION

The fourth generation of nuclear power is seen as a major step forward towards a more sustainable usage of nuclear power with respect to uranium resources, safety, economy and waste minimization. One of the main projects addressing these issues is the so-called "CFV" core concept in the ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration) project in France [1], which is developed to provide a full-scale demonstration of advanced sodium fast reactor (SFR) technology for commercial use.

In earlier SFR designs, one of the perceived drawbacks from a safety point of view was the positive sodium void coefficient. In the proposed CFV concept, a new axially heterogeneous core arrangement is proposed in order to make this sodium void coefficient less positive or even negative [1].

In the early 90s, in the newly built SUPERPHENIX, discrepancies in B_4C control rod worth between calculations and measurements of up to 25 % were observed [2]. To reduce these discrepancies, new methods were introduced for control rod cross-section homogenization [2]. With these new methods, discrepancies between calculations and measurements were brought down to +/- 5 %.

The improved method for control rod homogenization that was introduced, is based on the work by Rowlands and Eaton [3] and uses reactivity preservation instead of the more common reaction rate preservation.

This method takes into account the heterogeneous internal structure of the control rod, in a 2D radial model of the control rod with its immediate fuel environment, as in classical homogenization methods. However, it also includes the adjoint flux in the weighting process, in order to preserve the reactivity of the control rod. In doing so, preservation of the absorption rate in the rod is not guaranteed. This procedure will henceforth be referred to as the "(classical) equivalence procedure".

The situation is more complicated in the new axially heterogeneous concept of the CFV core, which is characterized by a lower fissile zone, an upper fissile zone, a thick fertile zone sandwiched between the fissile zones, and a sodium plenum above the fuel (see to the right in Fig. 1). The two fissile zones consist of MOX fuel, and the fertile zones of UOX. They are radially surrounded by a steel reflector.

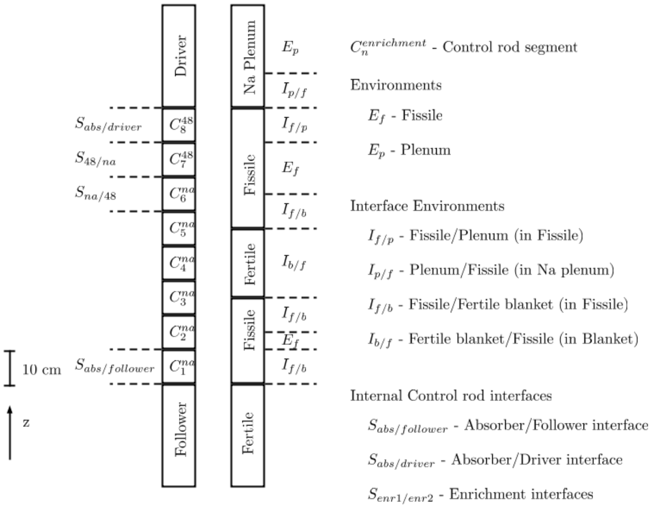

Fig. 1. Axial division of the control rod (left), the core (right), and definition of environments modeled.

These different axial zones, interface and material-conditions combined constitute a heterogeneous and computationally challenging control-rod environment, therefore putting homogenization methods to the test. In particular, it is unclear whether the performance obtained with the equivalence procedure for SUPERPHENIX still holds for such innovative cores.

In this work, a three-dimensional extension of the equivalence procedure has been developed to take better account of the varying environments in homogenizing the CFV core control rods. This numerical study is performed with the aim to investigate how well the classical equivalence procedure predicts the control rod reactivity worth and capture rates, in a representative CFV type core.

METHODOLOGY

The classical equivalence procedure [2] uses a *2D* (*X-Y*) S_N solver for the flux calculations, embedded in the ERANOS code package [4]. This *2D* is suspected to be insufficient to account for both radial and axial heterogeneities in the CFV core. Therefore, the equivalence procedure has been extended in the PARIS platform where a *3D* S_N solver SNATCH [5] can be used for the flux calculations.

By using this *3D* version of the equivalence procedure, the different environments in the CFV core can be modeled in a more representative way and environmentally-dependent homogenized equivalent-control-rod-cross sections can be derived more consistently than with a simpler *2D* model.

To reduce the number of cases to be investigated, some simplifications are needed in the axial representation of the control rods.

First, the 80 cm-long control rod absorber is subdivided into 10 cm long independent segments, as can be seen in Fig. 1. The absorber consists in two boron-10 enrichment zones, denoted by C1-C6 for the natural boron carbide in the lower part and by C7-C8 for the 48% B-10-enriched boron carbide in the upper part. Individual cross section sets are then derived for each 10 cm segments (see Fig.1).

The second simplification consists in neglecting the effect of a neighboring material if it is 10 cm away from the segment under investigation (Fig. 1).

The third and last simplification concerns control rod segments located further than 10 cm away in the sodium plenum; for those segments the same cross sections are used as for any 10 cm segment located far away from the fissile material.

The second and third approximations are justified on the basis of studies showing that these effects are negligible.

Core Calculation Methodology

In order to see the separate impacts of the sodium plenum, the fertile blanket and the axial heterogeneities of the control rod (absorber/follower and absorber/driver interfaces) on the results, each segment is treated separately and is added in sequence to the model.

The first case, denoted CLA, uses the classical approach where all segments are modeled with a fuel environment, which results in one unique set of homogenized cross sections. The second case, denoted ICE, introduces a *3D* modeling of the axial heterogeneities of the control rod, namely the absorber-follower and absorber-driver interfaces, which corresponds to C1 and C8 having separately treated cross sections, and C2 - C7 having the same cross sections as in CLA. In the third case, denoted PLE, the sodium plenum is added to the model and treated separately. When a control rod segment is located in these regions, environment-dependent cross sections are utilized. The fourth and last case, denoted BLA, takes into account the inner fertile blanket as an additional environment.

RESULTS

The core study was performed with the ERANOS code package and the continuous energy Monte Carlo code TRIPOLI 4 [6] as the reference solution, denoted T4, both with the JEFF-3.1 nuclear data library.

In order to separate the physical effects and to avoid modeling complications due to Doppler broadening and thermal expansions, the whole study was performed at room temperature.

The computed reactivities for the different cases are summarized in Tab. I, where all the control rods are in parking position, and in Tab. II for fully-inserted control rods. The difference between these two states (the total control rod worth) is summarized in Tab. III, in units of pcm.

Table I. Calculated reactivities for the control rods in parking position.

Case	ρ (pcm)	Δρ (pcm)	Δρ (%)
T4	6846	Ref	Ref
CLA	6550	-296	-4.32
ICE	6540	-306	-4.47
PLE	6553	-293	-4.28
BLA	6553	-293	-4.28

Table II. Calculated reactivities for fully-inserted control rods.

Case	ρ (pcm)	Δρ (pcm)	Δρ (%)
T4	3506	Ref	Ref
CLA	3360	-146	-4.16
ICE	3356	-155	-4.27
PLE	3436	-70	-1.99
BLA	3464	-42	-1.19

Table III. Calculated total control rod worth.

Case	ρ (pcm)	Δρ (pcm)	Δρ (%)
T4	3341	-	-
CLA	3190	151	-4.51
ICE	3184	156	-4.69
PLE	3117	224	-6.69
BLA	3089	251	-7.53

It can be seen in Tab. I that, in parking position, the error in reactivity compared to the Monte Carlo results is around 300 pcm, corresponding to about a 4% difference for all cases. On the other hand when the rods are fully inserted (Tab. II), the environment-dependent cross sections yield a better agreement with the Monte Carlo results (the BLA setup). It can also be seen that the most important contribution to this result is the special treatment of the region close to the sodium plenum.

The latter finding has two explanations: the higher enrichment of the boron carbide in the two topmost segments of the control rod, and the fact that the neutron spectrum changes significantly close to the sodium plenum.

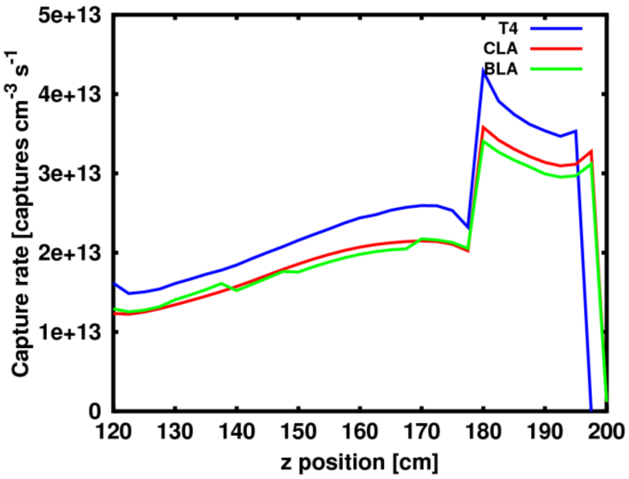

Fig. 2. Capture rates for a fully inserted control rod.

One reason why the discrepancy in the sodium plenum is very similar for all models, in spite of the differences in the treatment of the control rod, is the general difficulty that deterministic methods often have with transitions between heavy neutron-capturing media and light neutron-scattering media, in this case the core to sodium plenum interface.

A different effect can be seen in the control rod worth (Tab. III), where the classical approach offers the best prediction. This might seem surprising, but can be explained by the fact that, for the control rods in parking position, there is little influence of the environmental treatment on reactivity. Therefore, when computing the control rod worth by taking the difference in reactivities, there is a more favorable error compensation with the classical procedure.

The axial capture rate distribution for the fully inserted control rod (cases T4, CLA, and BLA) can be seen in Fig. 2.

In most cases, the environment-dependent cross sections BLA yield a worse prediction of the capture rates than the CLA, although only by a small amount since both cases under-predict the capture rates in all regions by 15-20%. This is not surprising since the equivalence procedure is not constructed to preserve capture rates, but reactivity.

CONCLUSIONS

In order to account for the variable environment of control rods in axially heterogeneous SFRs, a three-dimensional extension of the classical *2D* equivalence procedure for cross-section homogenization has been developed and tested against reference Monte Carlo calculations.

It has been found that, with the equivalence procedure expanded to three dimensions, a better prediction of the reactivity for different control rod positions within the core, in comparison with the classical two-dimensional approach, could be made (error reduction by a factor of up to 2). However, this *3D* procedure does not simultaneously improve the control-rod capture rate predictions.

Future work will include investigating different equivalence procedures, in order to better predict the capture rates. As sodium-voided configurations are also very important for CFV cores, they will also be included.

ACKNOLEDGEMENT

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