Improvement of advanced nodal method used in 3D core design system

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Abstract

This paper deals with AREVA NP progress in the modelling of neutronic phenomena, evaluated through 3D determinist core codes and using 2-group diffusion theory. Our report highlights the advantages of taking into account the assembly environment in the process used for the building of the 2-group collapsed neutronic parameters, such as cross sections or discontinuity factors.

The interest of the present method, developed in order to account for the impact of the environment on the above mentioned parameters, resides (i) in the very definition of a global correlation between collapsed neutronic data calculated in an infinite medium and those calculated in a 3D-geometry, and (ii) in the use of a rehomogenization method.

Using this approach, computations match better with actual measurements on control rod worth. They also present smaller differences on pin by pin power values compared to the ones computed with another code considered as a reference since it relies on multigroup transport theory.

KEYWORDS: Nodal Expansion Method, Rehomogenization

1. Introduction

Nowadays, most of 3D determinist core design systems are based on diffusion theory using advanced nodal methods in coarse mesh geometry. These advanced nodal methods are characterised by the introduction of discontinuity factors in order to enable equivalence between heterogeneous and homogeneous geometries, and the use of 2-group collapsed cross sections. The assembly neutronic data like collapsed 2-group cross sections, as well as the discontinuity factors used in these methods, originate from 2D single assembly transport calculations and thus do not take into account the assembly environment.

In the following, we introduce a method which allows taking into account the different environments of the assembly in the process used to compute the 2-group collapsed neutronic data. Evidently, because of calculation time, the aim is not to realise a high number of calculations on set of assemblies for instance. The 2-group collapsed neutronic data are modified by applying (i) a rehomogenization method for collapsed nodal cross sections, detailed in section 2.1 hereafter, and (ii) a correlation for discontinuity factors, detailed in section 2.2. Finally, section 3 is dedicated to the results.

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2. Method

2.1 Description of the rehomogenization method

In 3D core calculations using 2-group diffusion theory, the neutronic properties of the assemblies are defined by the collapsed cross sections, determined in an infinite medium. A consequence of this approximation is the use of an approximate flux weighing, especially in the case of assemblies containing control rods and surrounded by assemblies containing none. Obviously, in these conditions, the flux increase at the assembly boundary cannot be well described. As a result, the assembly collapsed cross sections are approximated.

The aim of the rehomogenization method [1] is to determine the impact of the different environment conditions on collapsed cross sections determined in an infinite medium and to correct them.

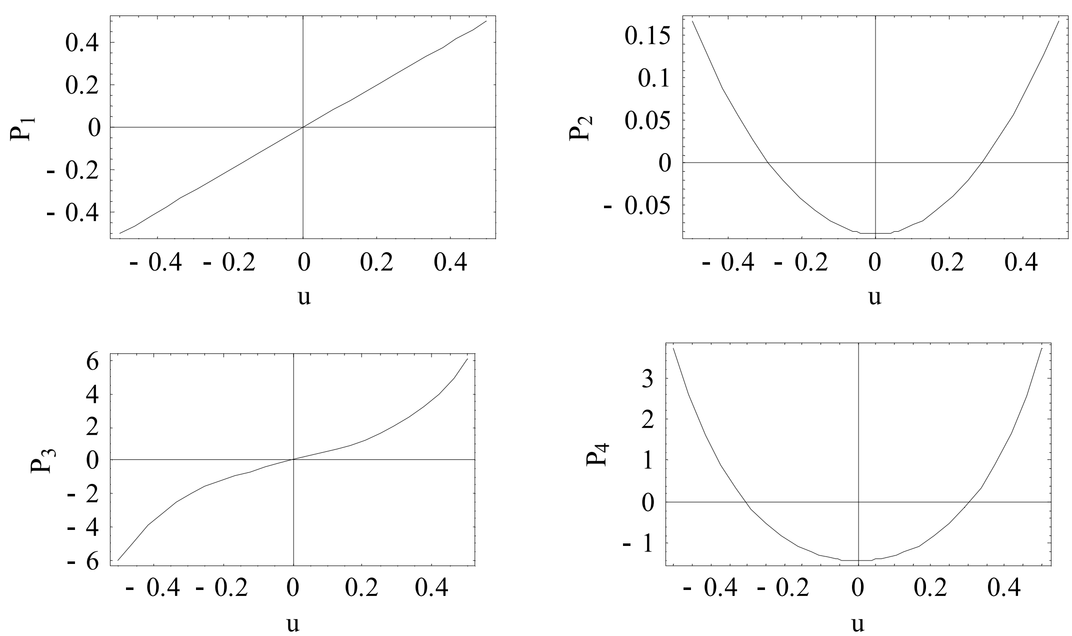
The idea to evaluate this impact is to consider the change in the flux shape between infinite and 3D conditions as an expansion of basis functions $P_i(u)$, which Fig. 1 illustrates. These functions are defined in the follow way. For the fast flux we have two basis functions:

$$P_1(u) = u, \quad P_2(u) = u^2 - \frac{1}{12}$$

and for the thermal group the same plus the following:

$$P_3(u) = \sinh(\eta u), \quad P_4(u) = \cosh(\eta u) - \frac{2\sinh(\eta/2)}{\eta}$$

Figure 1: Description of the basis functions $P_i(u)$ used for the expression of the flux variation between infinite and 3D geometry



Consequently, the flux variation calculated in an infinite medium and in a 3D-geometry, can be expressed by the following relationship:

$$\delta\Phi_g(r) = \sum_{d=x,y,z} \sum_{i=1}^{4} \alpha_{d,i,g} P_i(r) \qquad (1)$$

where g is the energy group and d represents the Cartesian coordinates (x, y, z).

The variation $\delta\Sigma_g$ of the collapsed cross section then reads:

$$\delta\Sigma_g(r) = \frac{1}{\overline{\Phi}_g} \sum_{d=x,y,z} \sum_{i=1}^{4} \alpha_{d,i,g} \delta_{d,i} \Sigma_g(r) \qquad (2)$$

where $\overline{\Phi}_g$ is the average assembly flux, $\delta_{d,i}\Sigma_g$ is the ith moment of the cross section Σ_g along direction d, defined as $\delta_{d,i}\Sigma_g = \int \Sigma_{d,g}(r) P_i(r) dV$ with $\Sigma_{d,g}(r) = \frac{\int \Sigma_g(r)\Phi(r)dV}{\int \Phi(r)dV}$.

Equations (1) and (2) in fact define the impact of the environment on the flux shape in the assembly and establish the correction which must be applied to the collapsed cross section. The coefficients $\alpha_{d,i,g}$ are computed by solving a problem similar to the equivalence problem in Nodal Expansion Method.

The interest of this method is twofold. The variation of the flux is easily determined during the 3D core calculations, since the effects of the environment on the collapsed cross sections are directly correlated to this variation. As a result, no change occurs in the process used to build 2-group collapsed cross sections in reflective boundary conditions and no added supplementary calculations are needed.

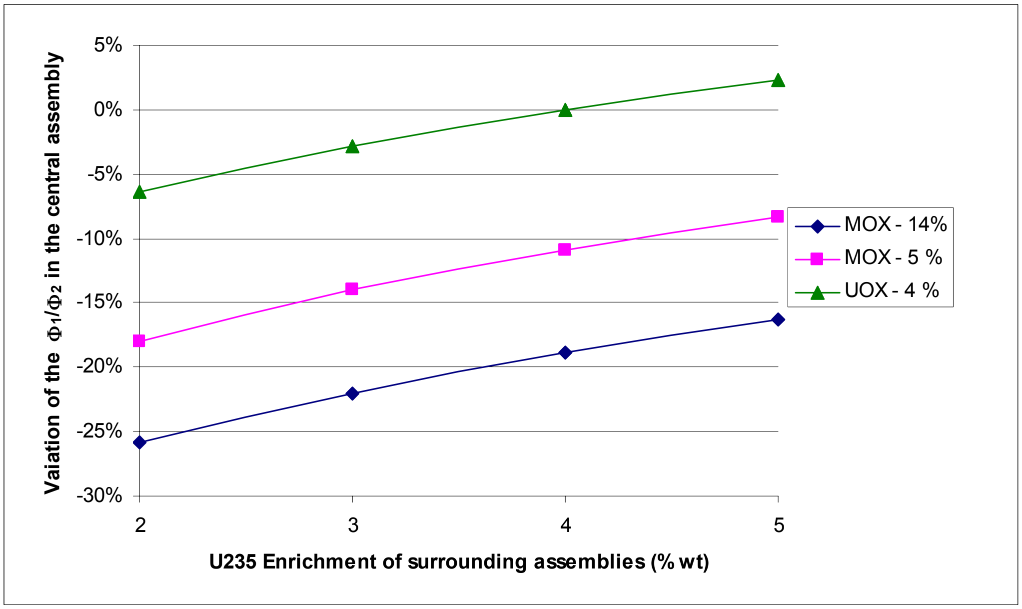
2.2 Definition of a global correlation between discontinuity factors determined in an infinite medium and on sets of assemblies

The role of the discontinuity factors in coarse mesh nodal calculations is important as they allow establishing the equivalence in terms of neutron exchange, between homogeneous and heterogeneous geometries. They reduce errors resulting from the use of classical homogenisation methods, which give no information whatsoever on the flux distribution [2]. However, the discontinuity factors remain approximations, as they are still determined *via* single assembly calculations unable to describe the real flux shape. In order to reduce the impact of this approximation, it is necessary to take into account the environment of the assembly in the process used to calculate these parameters. As was done for collapsed cross sections in section 2.1, we stress that our basic idea was not to increase the number of calculations on set of assemblies for each 3D nodal calculation, but to highlight a simple relationship we found between the discontinuity factors determined in an infinite medium and those determined in a 3D geometry.

The Φ_1/Φ_2 ratio is a fairly good parameter to evaluate the impact of the environment because it highly depends on the fuel rod enrichment, the assembly burn-up, the type of assembly and its environment. Fig. 2 shows the variation of this ratio according to the ^{235}U enrichment of the surrounding assemblies. One can note the large difference (up to 25%) between the

Φ_1/Φ_2 values evaluated for a MOX assembly in an infinite medium, and those calculated for a MOX assembly surrounded by 2wt% UO_2 assemblies.

Figure 2: Variation of the Φ_1/Φ_2 ratio in the central assembly according to the ^{235}U enrichment of the surrounding assemblies in set of assemblies geometry



The fact that ratio Φ_1/Φ_2 is highly dependent on that many parameters, led us to look for a simple relationship that would link the discontinuity factors calculated on single assembly and on set of assemblies, to the Φ_1/Φ_2 values determined in the corresponding situations:

$$ADF_{env} - ADF_{\infty} = F\left((\Phi_1/\Phi_2)_{env} - (\Phi_1/\Phi_2)_{\infty}\right)$$

where function F depends on the difference between the fast and thermal flux ratios determined both in an infinite medium (single assembly) and environmental condition (set of assemblies).

The value of the discontinuity factors ADF_{env} having been used to determine the variations for the best fit calculation which made it possible to determine function F were obtained by resolution of a nodal equivalence problem. This problem consisted to calculate intranodal flux forms by resolution of a linear system of 10 equations for each direction (x and y): 2 of neutron balance (fast and thermal), 4 of cancellation of the order 1 and 2 residuals of the flux, 4 of conservation of the current at the interfaces of the node calculated by the transport code APOLLO2 in set of assemblies condition. The currents in a direction were also used for the determination of the transverse leakage which appears in the neutron balance equations. Homogeneous surface fluxes (indicated by $\Phi_{surf,\text{hom}}$) which rise from the solution of these systems made it possible to calculate the discontinuity factor by the relationship:

$$ADF_{env} = \frac{\Phi_{surf,het}}{\Phi_{surf,\text{hom}}}$$

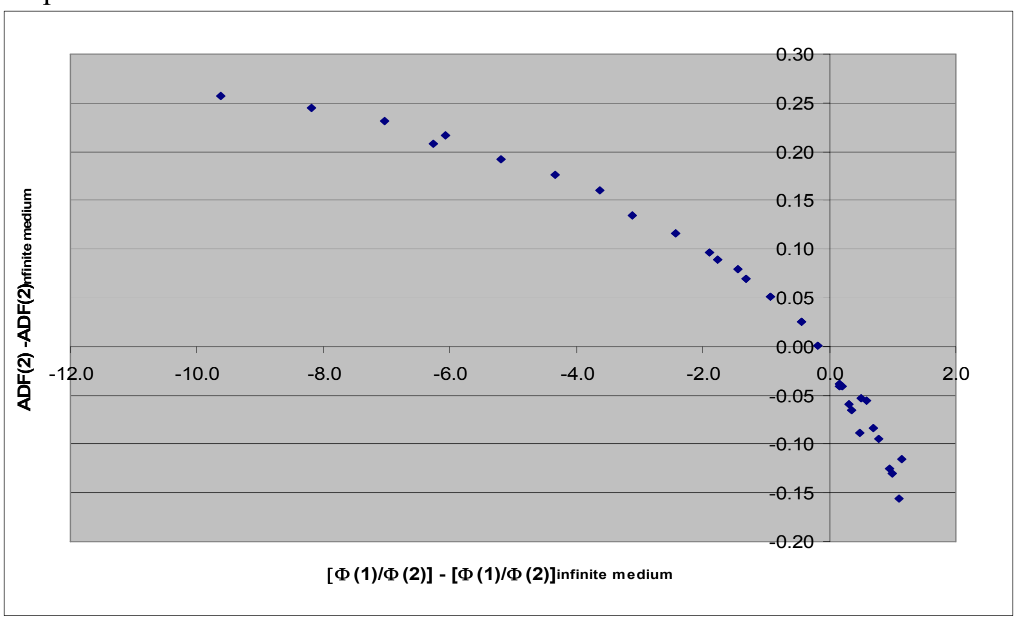
where $\Phi_{surf,het}$ is the heterogeneous surface flux from the set of assemblies calculation.

The shape of function F is shown in Fig. 3. This function is relative to the discontinuity factors for thermal group. It shows a simple correlation between the variation of the discontinuity factors calculated in an infinite medium and in sets of assemblies, and the associated difference in the values of the Φ_1/Φ_2 ratio. The points are the results of assembly set calculations (followed by the resolution of the equivalence problem described above) with varying ^{235}U enrichment and Pu isotopes densities. This function can be easily programmed in a 3D nodal core code. For 3D nodal core applications the $(\Phi_1/\Phi_2)_{env}$ value will be replaced by the ratio of average nodal fluxes and ADF_{env} will be approximated by the value interpolated on the basis of function F. As far as ADF_∞ is concerned, its value is computed during the collapsed cross section library building process. The infinite medium fast to thermal flux ratio is computed by the relationship:

$$(\Phi_1/\Phi_2)_\infty = \frac{\Sigma_{a,2}}{\Sigma_r}$$

where $\Sigma_{a,2}$ and Σ_r are the thermal absorption and removal from fast to thermal cross sections respectively.

Figure 3: Shape of the correction factor F function of differences on fast and thermal flux ratio



3. Results

For evaluation, these developments have been tested in a beta version of SMART code [3]. These improvements have been evaluated on comparisons between APOLLO2 [4] and SMART pin by pin power distributions on a set of MOX and UO_2 assemblies and through control rod worth calculation versus measurement comparisons (C/M).

The impact of the new evaluation of the discontinuity factors has been determined on a set of MOX and UO_2 assemblies (Fig. 4). This geometry is representative of the impact of the environment on UO_2 assembly due to the decrease of the pin power at the boundary of the assembly near the MOX assembly (Fig. 5).

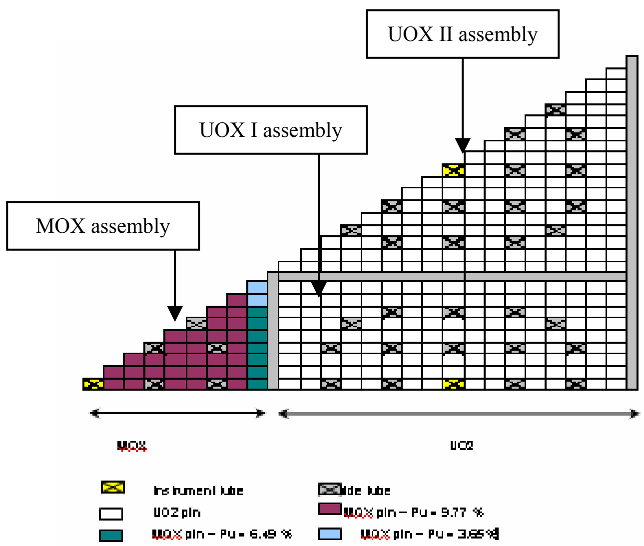


Figure 4: set of MOX and UO_2 assemblies

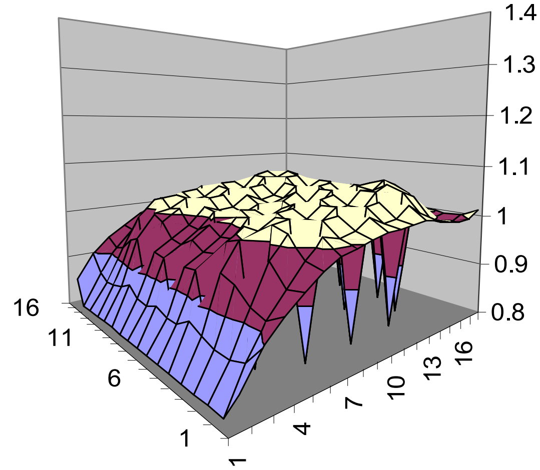


Figure 5: Pin power decrease on UO_2 assembly at the MOX/ UO_2 boundary

The environment effects applied on the infinite medium discontinuity factors through the function *F* allow reducing SMART/APOLLO2 maximal differences (Tab. 1) on pin power to less than 1 % in UO_2 assemblies notified UOX I which corresponds to the UO_2 assembly in front of the MOX assembly (see Fig. 4). As far as standard deviations are concerned, they are lower than 0.3 % in UOX I, which demonstrates a better modelling of MOX and UO_2 interfaces. The mean difference at the UO_2/MOX boundary is reduced to -0.1 % and 0.4 % in the MOX and UO_2 assembly respectively (see Fig. 5) instead of -1.0 % and 1.5 %.

Table 1: Impact of environment corrections on pin power distribution

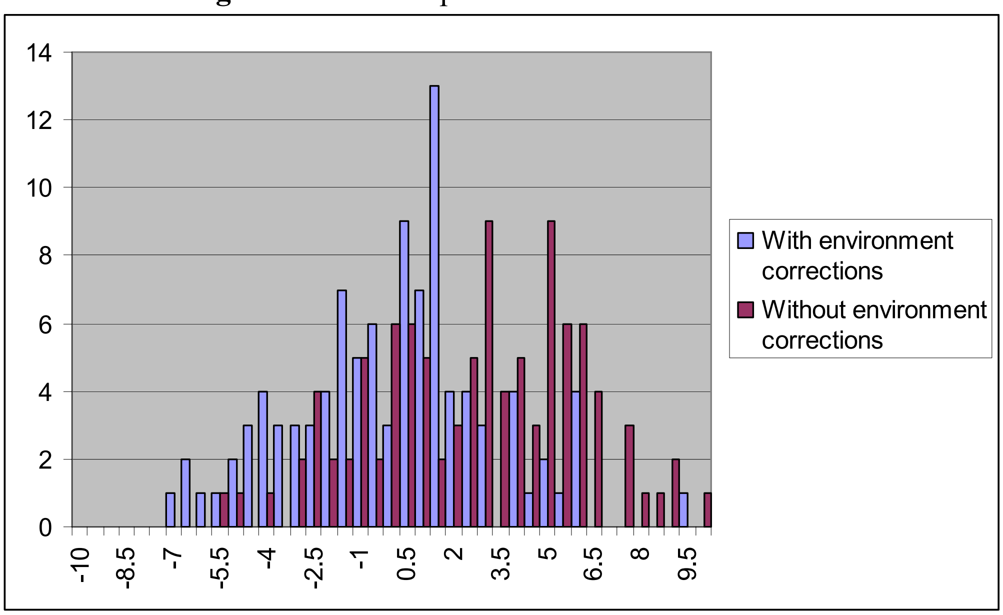
	MOX / UOX - Cluster					
	MOX		UOX I		UOX II	
	Max. difference (%)	Standard deviation (%)	Max. difference (%)	Standard deviation (%)	Max. difference (%)	Standard deviation (%)
Without environment correction	1.96	0.93	1.92	0.5	1.46	0.22
With environment correction	1.83	0.62	0.76	0.26	0.84	0.21

Figure 5: SMART/APOLLO2 differences on pin power for a UO_2/MOX set of assemblies with environment corrections.

																										-0.1
																									-0.1	-0.1
																								-0.1	-0.2	-0.1
																							X	0.0	-0.1	-0.1
																						0.0	0.1	0.1	-0.1	-0.1
																					X	0.0	0.0	X	-0.1	-0.1
																				-0.1	0.1	-0.1	-0.1	0.0	-0.1	-0.1
																			0.1	0.0	-0.2	-0.1	0.0	-0.2	-0.1	0.0
																		X	0.0	0.1	X	0.0	0.1	X	0.1	-0.2
																	0.6	0.2	0.1	0.0	-0.1	0.0	0.0	-0.2	0.0	0.0
																0.3	0.4	0.4	0.1	0.0	0.1	-0.1	0.0	0.1	0.0	0.1
															X	0.3	0.2	X	-0.1	0.1	X	0.1	0.1	X	0.1	0.0
														0.1	0.2	0.1	0.3	0.3	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.0
													X	0.1	0.1	0.0	0.2	0.3	0.1	0.0	0.1	0.2	X	0.1	0.0	0.0
												-0.2	-0.1	-0.1	X	-0.1	-0.1	X	-0.1	0.1	X	0.1	0.1	0.0	0.0	0.1
											0.0	-0.2	-0.4	-0.4	-0.4	-0.4	-0.2	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.1
										0.8	0.2	-0.3	-0.6	-0.8	-0.7	-0.6	-0.3	-0.1	0.1	0.1	0.1	0.0	0.1	0.0	0.0	0.1
								1.8		0.7	0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.3	-0.3	-0.2	-0.2
							-0.9	1.0		-0.1	-0.2	-0.1	0.1	0.2	0.4	0.1	0.0	0.1	-0.2	-0.2	-0.1	-0.1	-0.2	-0.3	-0.3	-0.3
						0.7	0.3	-0.3		0.5	0.0	0.1	0.3	0.5	X	0.4	-0.1	X	-0.2	0.0	X	-0.1	-0.1	-0.3	-0.3	-0.3
					X	0.4	0.3	-1.0		0.7	0.4	0.4	X	0.5	0.5	0.3	0.1	0.0	0.0	-0.1	-0.1	0.0	X	-0.1	-0.2	-0.2
				-0.4	-0.7	-0.3	0.0	-1.1		0.8	0.4	0.5	0.6	0.5	0.5	0.2	0.0	0.0	0.0	-0.1	-0.1	-0.1	0.0	-0.1	-0.1	-0.2
			X	-0.4	-0.7	X	-0.7	-0.8		0.6	0.4	X	0.5	0.5	X	0.2	-0.2	X	-0.2	0.0	X	0.0	-0.1	X	-0.2	-0.2
		0.1	-0.4	-0.2	-0.3	-0.3	0.3	-0.5		0.3	0.3	0.4	0.4	0.3	0.2	0.0	-0.2	-0.2	-0.1	-0.1	-0.1	0.0	-0.1	0.0	-0.1	-0.2
	0.9	0.4	0.0	0.1	0.2	0.2	0.7	-0.1		0.2	0.2	0.2	0.2	0.1	0.0	-0.2	-0.4	-0.5	-0.2	-0.2	0.0	-0.1	0.0	0.0	-0.2	-0.2
X	1.1	0.4	X	0.2	0.0	X	0.3	0.3		0.3	0.1	X	0.1	0.0	X	-0.2	-0.6	X	-0.4	-0.1	X	0.1	0.0	X	0.0	-0.2

As far as the impact of the rehomogenization method is concerned, it has been determined by calculation against measure (C/M) comparisons on control rod worth values representative of 900 MWe and 1300 MWe reactors. These comparisons are performed on one hundred C/M differences and Fig. 6 shows the C/M distribution. One can note that the maximum difference is nearly 1%. The C/M absolute mean difference is 0.5% lower, 90% of the differences are lower than 5% in absolute value and 55% are comprised in a range of ±2% instead of 75% and 30% respectively.

Figure 6: C/M comparisons on control rod worth



4. Conclusions

In conclusion, it must be noted the significant improvement given by these developments to get collapsed neutronic data taking into account the real in-core environment surrounding the nodes in advanced nodal 3D calculations. The methods developed here apply only 2-group diffusion problems.

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