APOLLO2 : test of recently implemented methods applied to the calculation of a large scale heterogeneous cluster

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ABSTRACT

This article herein presents a review of different deterministic methods integrated in the APOLLO 2 code. They are applied to the calculation of a large cluster.
We used, for solving the neutron transport equation, the collision probability (Pij) method, a recently implemented Characteristics method as well as the so-called two-level scheme (TLS). Those methods and schemes have been run for calculating a large and heterogeneous cluster representing a usual French PWR lattice configuration.
The various results are compared against a precise Monte Carlo simulation. The k infinite and the absorption rate have been chosen as relevant quantities for the comparison.

1. INTRODUCTION

Apollo 2 [1,2] is a French modular code aimed at solving the Boltzmann transport equation in a great range of lattice configurations. It has been developed by the "Commissariat à l'Energie Atomique" with the support of Framatome ANP and EdF. These two companies as well as the CEA use the Apollo 2 code for their lattice neutronic calculations [3,4].
Beyond the neutronic flux calculation methods, Apollo 2 contains a modern self-shielding model, procedures for critical buckling treatment and for transport/transport equivalence. Moreover, numerous types of geometry can also be described.
As far as flux calculation is concerned, various methods are available in Apollo 2. The collision probability (Pij) method is commonly used with a cylinderization (multicell) approximation in most of the industrial contexts. This method is actually fast but it is expected to provide improvable estimates in very heterogeneous configurations where the flux gradient is important.
A Sn solver is also accessible in Apollo 2. The flux variation is treated in a better way and the anisotropic scattering can be taken into account. Unfortunately, the computation time becomes quickly prohibitive while refining the energy and spatial meshing.
A new characteristics method [5] has been recently implemented in the release 2.6 of the Apollo 2 code. This solver allows the treatment of the anisotropic scattering. However, like in the Pij case, the flux is flat within a single spatial mesh.

This work aims at comparing the quality and the performance of various calculation schemes exploiting the previously quoted methods.
Every deterministic calculation will be compared to a reference Monte Carlo simulation provided by the Tripoli 4 code[6,7]. This simulation is described in section 3.

2. FUEL DESIGN

The chosen cluster design is illustrated in Figure 1. Exploiting the various symmetries, its size amounts to 171 cells. 21 cells are Guide Tube cells and the other 150 are fuel cells. The cluster is heterogeneous since the central part fuel is composed of MOx cells (mix of uranium and plutonium oxides) while the other fuel pins are classical UOx's. The Pu content of the Mox pins varies (from 3 to 6wt%) depending on the position in the central assembly. The enrichment of the Uox pins amounts to 3.25wt%. The water gap between each assembly is explicitly described. This design is of special interest since many French PWRs are at the present time loaded with both Uox and Mox assemblies.

The fuel heterogeneity of the cluster induces a large flux gradient around the fuel interfaces. We actually expect the neutron flux to be much more energetic in the MOx region than in the UOx part of the cluster. The main challenge of the tested calculation methods lies in their ability to reproduce this major flux gradient properly.
A dashed line shows the boundaries of the pattern. We chose to compute each calculation with reflected boundary conditions. Indeed, to make the Apollo 2 results comparable with the Monte Carlo simulation, no leakage could be accounted for.

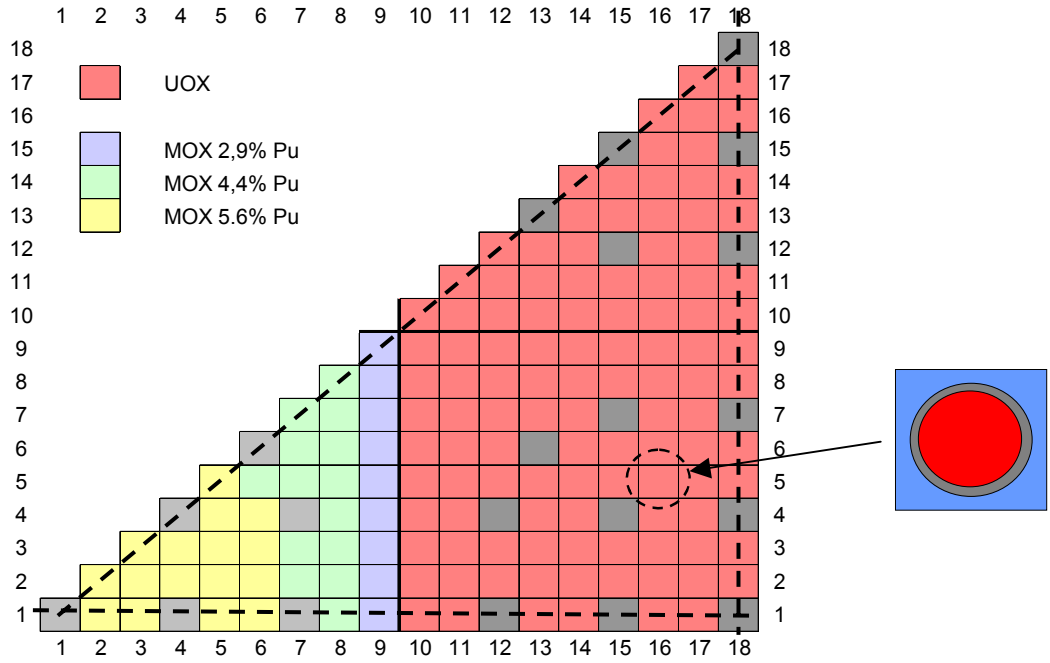

Figure 1. Cluster design. The 171 cell cluster. 21 Guide tube (in grey). 39 Mox cells (in blue, green and yellow depending on the Pu content) and 111 Uox cells (in red). Fuel, cladding and water is represented. The fuel pin is divided into 6 concentric calculation meshes (not represented).

3. THE MONTE CARLO SIMULATION

Tripoli 4 is a Monte Carlo type simulation code especially dedicated to the transport of neutrons and the electromagnetic radiation. It is able to provide a k infinite as well as reaction rates estimates. The exploited cross sections are taken from the JEF 2 evaluation. The number of propagated neutrons amounts to 66 millions allowing a refined estimate of the k infinite and absorption rates (see Figure 2 the calculated absorption rates and Figure 3, the associated standard deviations.) Those rates are condensed to 2 energy groups (see table 1.) The produced reaction rates are integrated over the whole cell volume.

Table 1. Boundaries of the energy groups

Group	Upper energy (eV)	Lower energy (eV)
1	10^{7}	0.625
2	0.625	10^{-11}

The estimated k infinite amounts to **1.24521** (σ = 14 pcm.)

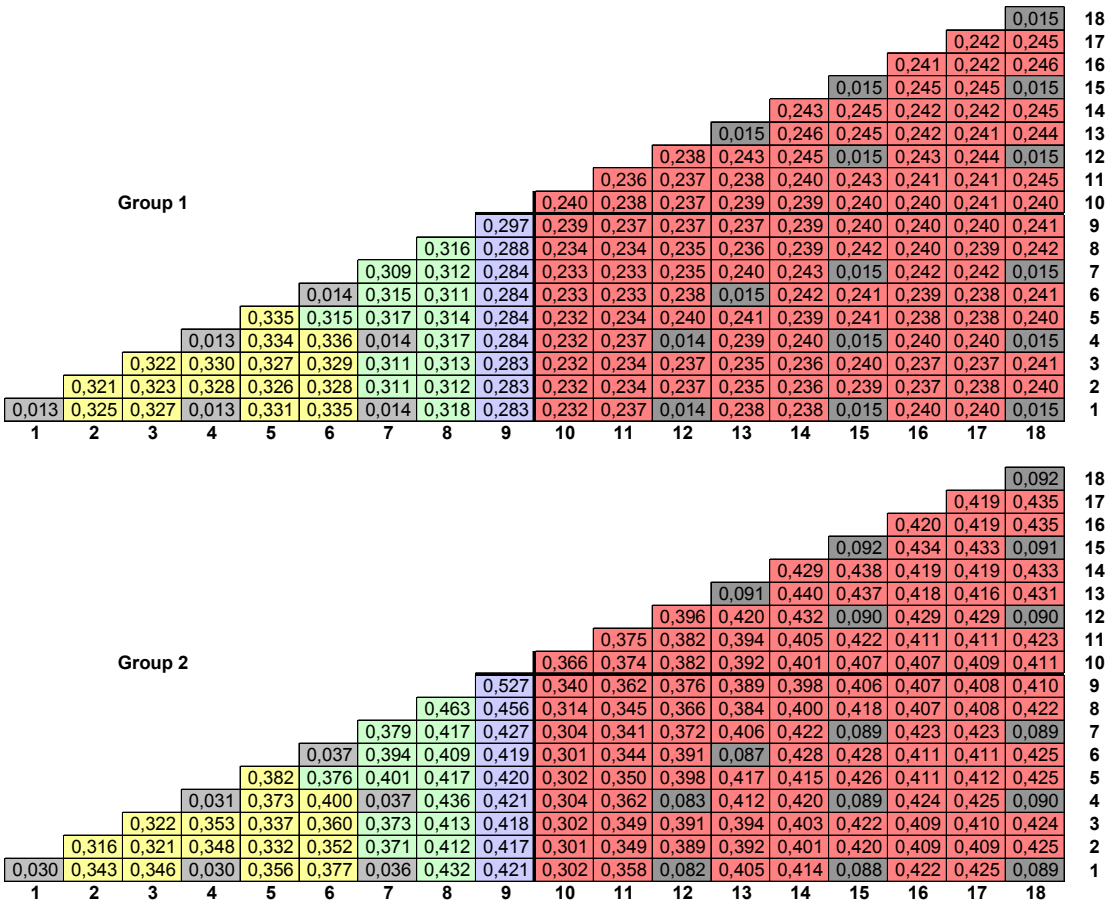

Figure2. Tripoli 4 absorption rates. The sum of all rates is normalized to 100.

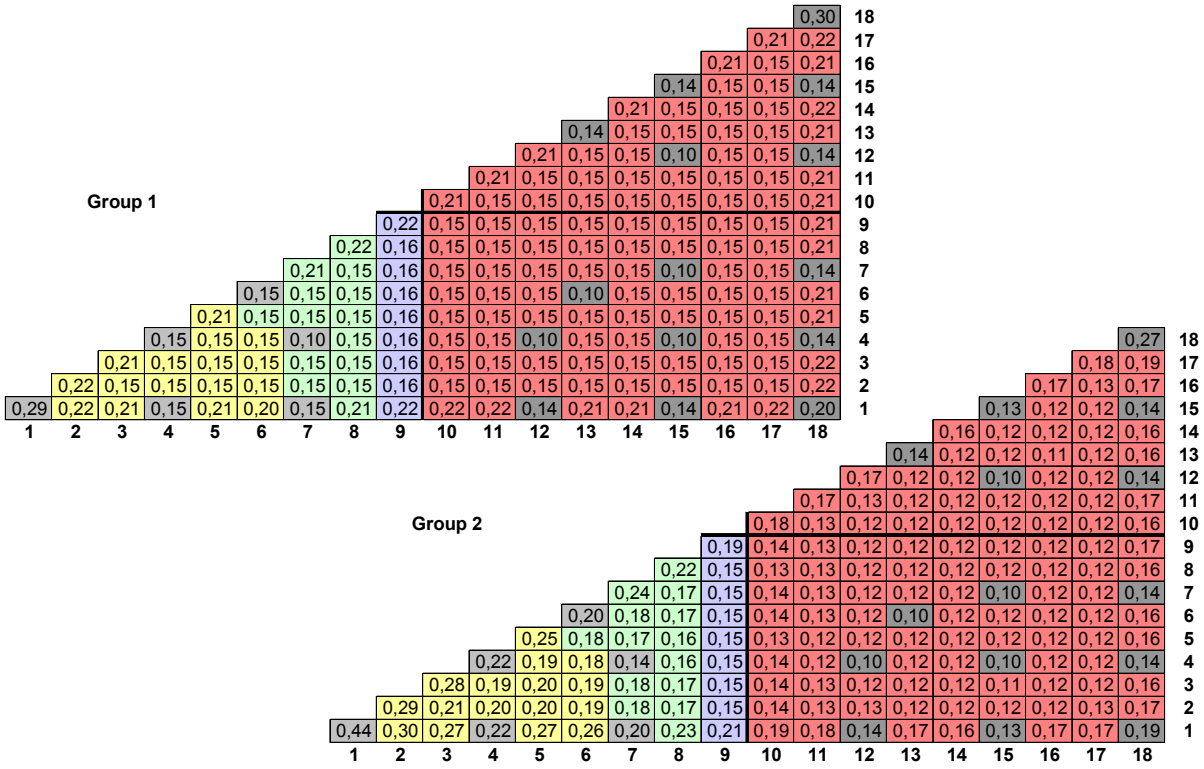

Figure 3. Tripoli 4 absorption rate - standard deviations (in %).

4. THE APOLLO 2 CALCULATIONS

This section presents the performed APOLLO 2 calculations. At first we give an overview of the general structure of the calculation schemes. We present every method in the following sub-sections.

4.1 GENERAL CALCULATION SCHEME

The cross-section library is the usual CEA93 release 6, with 99 group energy meshes. The detailed geometry is described (see figure 1.).
The fuel pins are divided into 6 concentric spatial meshes in order to follow the important flux gradient within the pin. The self-shielding is performed by using the standard APOLLO 2 model [8]. As a result, a set of 99 group cross-sections is produced for all rings of every pin cell. Those cross-sections are transmitted to the different deterministic solvers.

4.2 PIJ MULTICELL

Most codes are using the Pij method for solving the integral form of the transport equation. In this formalism, every cell “communicates” with their four neighbors through an interface current. The collision probabilities are computed for each individual cell. This method includes a flat flux approximation within a single spatial mesh. Therefore, it is necessary to divide all fuel pins into several (4 in our case) spatial meshes. However, the cylinderization included in the multicell approximation restricts the realism of the method in case of major flux between adjacent cells.

The calculation with the Pij multicell method is very fast (see table 2.) The obtained k infinite is **1.24387**, 134 pcm below the Monte Carlo value. In this sense, the agreement is pretty good. However, looking at the figure 4 we notice that the discrepancy between the reference absorption rates ant those from the Pij multicell method are quite important. Indeed, we observe around 6% disagreement in the thermal group close to the MOx-UOx interface. This disagreement was expected considering the important flux gradient in this region (see the Monte Carlo absorption rates in figure 2.)

We observe that the Pij multicell model is not able to precisely represent such a major flux gradient. The Two Level Scheme (TLS) was also tested. The following section illustrates the obtained results.

Table 2.Computation times for the various tested codes and methods.

Code	Method	Computation time (s)
Tripoli 4	Monte Carlo	$6.9*10^6$
Apollo 2	Pij Multicell	200
Apollo 2	TLS	700
Apollo 2	Characteristics	$1.8*10^4$

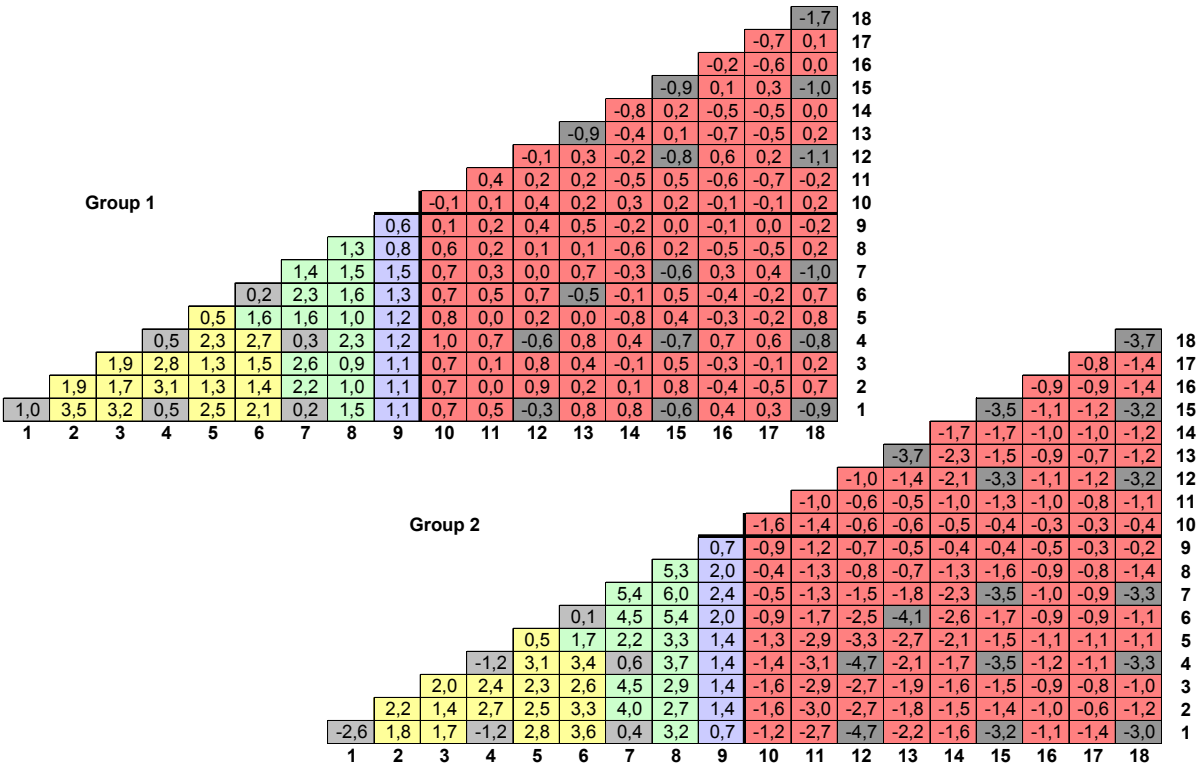

Figure 4. Discrepancy between Pij Multicell and reference absorption rates (in %).

4.3 THE TWO-LEVEL-SCHEME (TLS)

The TLS is extensively described in [9,10]. The first part of the calculation is a full Pij multicell calculation as described in the previous sub-section. The Pij solution of the transport equation is therefore used to condense the 99 group energy grid into 6 groups only. We also proceed an homogenization which reduces the number of spatial meshes from 8 per cell to a single one.

Those condensation and homogenization are performed through an equivalence procedure [11,12,13]. This way, the number of spatial and energetic meshes is strongly reduced allowing the use of the Sn solver as a "second level". This way, we expect a better treatment of the long-range flux gradient than previously. The Sn solver of Apollo 2 is of nodal type treating one point per spatial mesh. Moreover, the low number of spatial and energy meshes permits reduced computation times.

The TLS provide a k infinite of **1.24398** very close to that obtained with the Pij multicell approximation and around 120 pcm far from the reference calculation. Figure 5 shows the discrepancy between the Monte Carlo calculation absorption rates and the TLS. The results are much more satisfactory than before. The important disagreement observed in the thermal group is almost fully washed out.

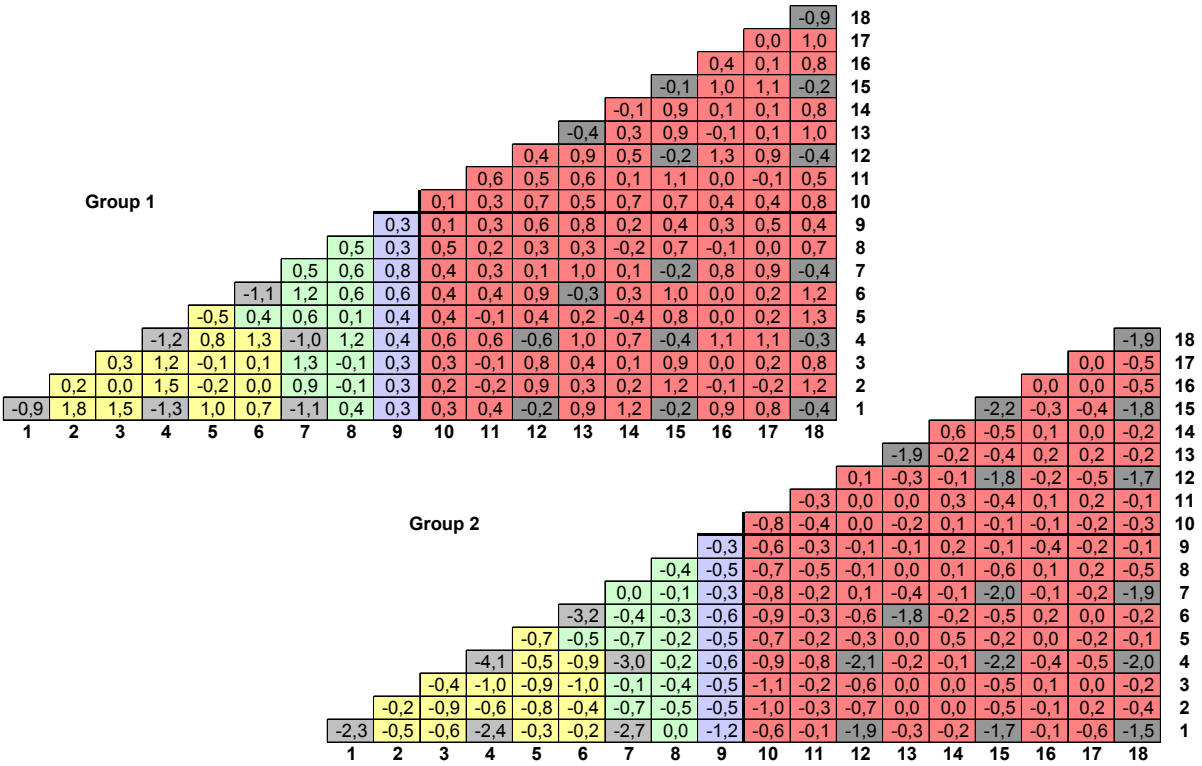

Figure 5. Discrepancy between the TLS and the reference absorption rates (in %.)

4.4 THE METHOD OF CHARACTERISTICS

A method of Characteristics has been implemented in the latest version of Apollo 2 (Apollo 2.6.) This method is tested here for the first time in an industrial context. As in the Pij case, the flux is assumed to be flat within each spatial mesh. Nevertheless, compared to the Pij calculation, we increased, for the Characteristics calculation, the number of spatial meshes, dividing the cells into 4 sectors as seen figure 6. Moreover, the Method of Characteristics accounts for the anisotropic scattering.

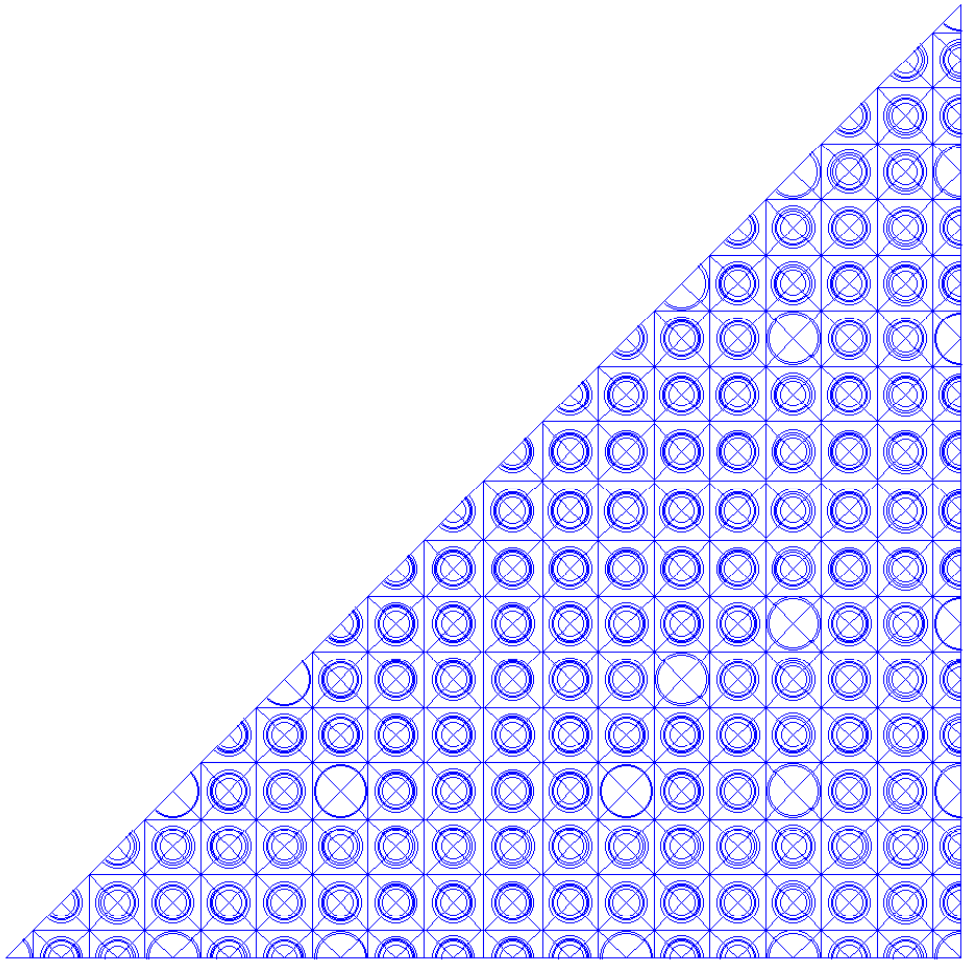

Figure 6. Spatial meshing for the Characteristics calculation.

The total number of spatial meshes amounts to 3500 (Figure 6). We exploited the set of cross section coming from the self-shielding procedure (99 group cross-sections.) The method provides a k infinite of **1.24390**. This value is close to that obtained with the other methods of Apollo 2 and is about 130 pcm far from the reference value. A survey of the absorption rate chart (Figure 7) shows that the agreement is rather good in almost all fuel cells; the observed discrepancy appears lower than 1% in most cells and both energy groups.

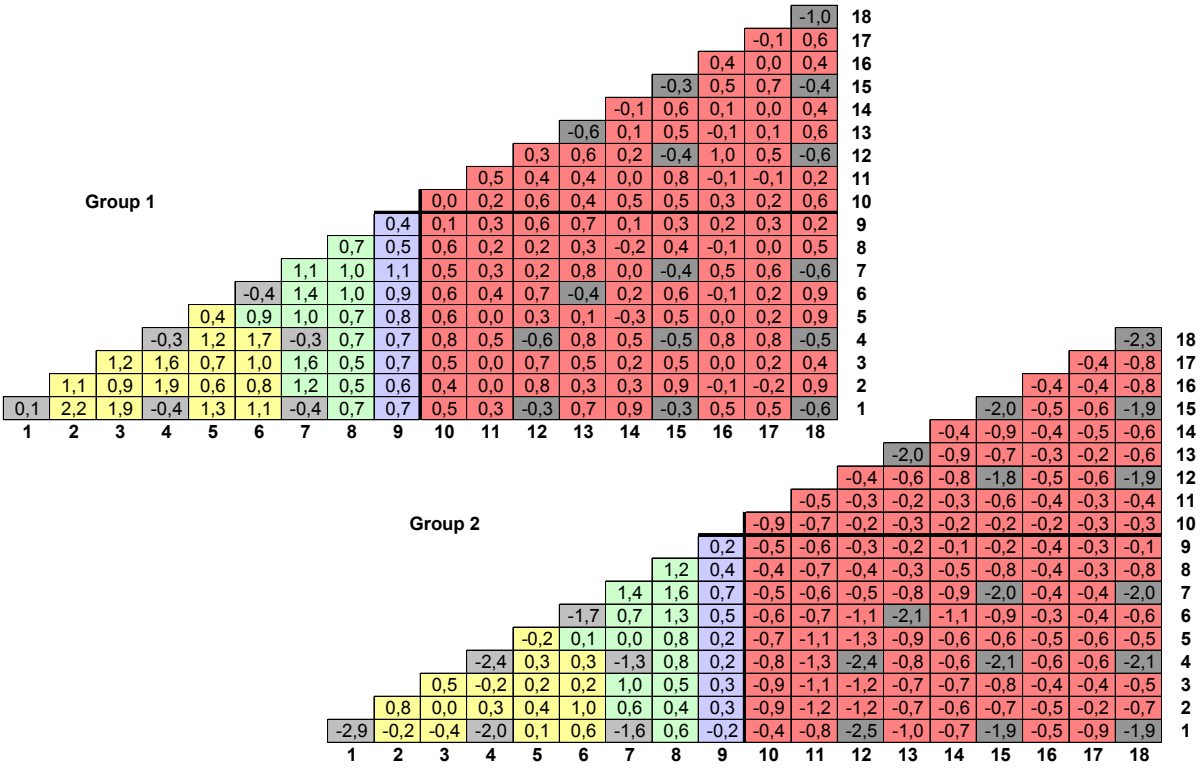

Figure 7. Discrepancy between the calculation by the Method of Characteristics and the reference absorption rates (in %.)

CONCLUSIONS

We studied the neutronic behavior of a large and heterogeneous cluster. We applied various calculation methods available in the Apollo 2 code. All results were compared to a precise Monte-Carlo simulation. The different deterministic methods provided a good estimate of the k infinite. However, the standard and fast Pij - Multicell method exhibited an improvable ability in reproducing the absorption rates. On the other hand, the Two Level Scheme and the newly implemented Characteristics method provided accurate and promising results.

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