Deterministic and Monte-Carlo calculation schemes of the EPR core and its heavy steel reflector

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1. INTRODUCTION

In the framework of the growth of nuclear power and of the replacement of existing plants in the XXIst century, new concepts, safer and more efficient, have been developed by industry, like the European Pressurized Reactor (EPR). Although these concepts carry on with the continuity of plants today in operation, some technological innovations need efforts of R&D. In particular, the choice of a heavy reflector surrounding the core requires developments and validations of new calculation schemes to take into account the important quantity of steel and its neutronic effects. More, large memory computers allow performing large scale calculations of LWR cores using heterogeneous transport methods, both with Monte-Carlo and deterministic codes.

The aim of this work is to study an EPR core and its heavy reflector with the objective to quantify both the methodological biases within three calculation schemes and the impact on the core neutronic behaviour of the heavy reflector. To reach this, three different calculation schemes are presented here:

- A reference calculation using the pointwise Monte-Carlo TRIPOLI4 code [3]
- A deterministic one, fully heterogeneous, based on the method of Characteristics implemented in the APOLLO2 code [1]
- A diffusion approach using the mixed-dual finite elements with the CRONOS2 code [2]

The first part of the paper gives the main characteristics of the core configuration chosen for the analyses. In a second part, the three different models and schemes are described and the third part is dedicated to the analysis of the results.

2. PHYSICAL AND TECHNOLOGICAL PARAMETERS

Calculations have been achieved with a 2D model of an eighth of the core in which each cell has been described (with its fuel, poison, clad and moderator elements). In all cases, the beginning of a cycle with an out/in fuel management is considered. This loading pattern (cf figure 2) includes four types of UOX assemblies (from fully new ones to beginning of 5th cycle) and three types of UOX-Gd assemblies (from new ones to beginning of 4th cycle). The 1st cycle UOX fuel rods have a ^{235}U enrichment of 4.9%. Brand new gadolinium assemblies contain 12 rods poisoned up to 8% in Gd_2O_3 in depleted uranium.
The 2 types of assemblies are presented in figure 1. The EPR assembly is constituted by 265 fuel rods and 24 guide-tubes. Notice that the central rod doesn't contain instrumentation tube but a fuel rod.
The figure 2 shows the core description with the location of gadolinium and standard assemblies and the position of control rods. The heavy reflector is essentially composed of

stainless steel. Different layers of stainless steel with water dilution, to simulate the water holes (for baffle cooling) follow the boundaries of the fuel core.

The depletion of fuel has been performed with a core power of 4250 MW for a 422.5 cm active length. The main characteristics of the fuel rods are gathered in table 1.

3. CODES AND MODELLING

The different modeling presented in this paper are, on one hand, the CEA pointwise Monte-Carlo code TRIPOLI4 [3] and, on the other hand the CEA reactor physics codes APOLLO2 and CRONOS2 [1], [2].
APOLLO2 is a spectral code which solves the Boltzman transport equation and is based on a multigroup cross-sections database. This database is here provided by JEF2.2, and produced by NJOY and specific modules; it is completely coherent with the nuclear data used in the TRIPOLI4 simulation. APOLLO2 commonly uses 172 energy groups but is also able to use any energetic meshing ranged from several hundreds of groups to several thousands of groups.
CRONOS2 is dedicated to core calculations, solves transport or diffusion equations and is interconnected with APOLLO2 via multiparametrized cross sections libraries.

The reference simulation of the EPR core is a pointwise pin by pin Monte-Carlo calculation. The nuclear cross sections associated to the materials in the core are pointwise data derived from the JEF2.2 evaluation. The compositions of the different fuel assemblies at different burnup are obtained with an APOLLO2 depletion calculation for which the assembly in infinite medium is considered and where the isotopic densities are averaged from 5 zones per pin for standard fuel assemblies and from 7 zones per pin for gadolinium assemblies
The core geometry is represented by a 1/8 symmetry; the boundary conditions are reflection on the 2 axis of symmetry and leakage at the edge of the reflector. To keep the consistency with the deterministic models, the cooling water holes of the reflector are diluted in the stainless steel with various dilution factors versus the distance from the fuel core.
Globally, the geometry is constituted by 30000 meshes, which leads to a very ambitious simulation, especially to obtain accurate and precise responses in term of reactivity and local reaction rates. Thanks to the capability to use the parallelization mode implemented in TRIPOLI4, the CPU time is drastically reduced to one week for execution time. For this simulation, 700 millions of neutrons have been propagated, that allows to reach an uncertainty of 3σ of 13 pcm on the reactivity. Averaged reaction rates on quarter of assembly and local rod by rod reaction rates are computed respectively with a deviation of 0.2% and 1%. Such a calculation, using 700 millions neutrons, takes about 6 days on a standard cluster of 5 standards PC Linux.

The second scheme of this analysis, is based on the *Method of Characteristics* implemented in the spectral code APOLLO2 [1]. This method [4] allows to take into account the anisotropy effect in the cross sections. Very efficient acceleration methods have been recently implemented [5], which allow the computation of large cores. So, this method is well adapted to treat flux and spectra transients for example at the interface between the core and the reflector.
To obtain accurate converged results, the method needs to describe very fine tracking lines, a convergence analysis is always necessary to reach a good level of convergence in term of flux keeping an interesting CPU cost.
In this core calculation, all detailed pins are represented, and the reflector is precisely described (it doesn't use a homogeneous representation). About 60000 meshes have been defined, this represents a big challenge for the APOLLO2 code both in term of CPU time and memory space. Such a calculation, using a 172 group library, takes 72 h and a memory of 11

Go on a standard 2 GHz PC Linux. Here the usual use of spectral codes is exceeded, usually used for assembly calculations and not for core geometries. However, results for core computation have been shown and commonly presented [8], [9].
The fine mesh is defined on the pin cell and illustrated in figure 3, each rod is described, the meshing for the assemblies close to the reflector is refined to take into account the flux gradients at the core/reflector interface. To obtain a satisfactory convergence, the last new developments in the numerical scheme based on multigrids methods are used [5] in addition to the capability to implement a different tracking for each energy group.
Before the flux calculation, the compositions of the different fuel rods are introduced and the self-shielded cross sections computed by independent depletion assembly calculations are used (as for TRIPOLI4 input compositions, this ensures the coherence of the two calculations). For the reflector, the self-shielding effects on iron, nickel and chromium atoms contained in steel are taken into account.

The third calculation scheme uses the principle of the two group diffusion in the core code CRONOS2 [2]. This scheme is very close to an industrial approach; it is based on two major steps: first, the fuel element is calculated in 2D transport theory in its heterogeneous representation using the APOLLO2 spectral code with a very fine energy meshing (172 groups). Then, this calculation provides condensed (2 groups) and homogenized cross sections to the core code CRONOS2, which performs 3D calculations in diffusion theory with finite-elements. In the case of EPR core, about 11000 calculation meshes are required
For the reflector, the CEA method [6] is used; its objective is to reproduce the neutron exchanges at the interface between core and reflector. In this approach, an equivalent homogeneous reflector is calculated to comply with a matrix of reference albedos obtained by the Monte-Carlo code TRIPOLI4. The geometry considered to achieve the equivalence process is 1D and constituted by some layers of fuel, stainless steel and water diluted in steel.

Finally, the coherency between the three core calculations was kept, since single APOLLO2 calculations give both the material compositions (depending on the burn-up) to TRIPOLI4 and the description of the materials and self-shielded cross sections to the full core APOLLO2 MOC computation and to the 2 group diffusion calculation in CRONOS2. In the same way, the spatial meshing comes from the same graphic tool, SILENE, for both APOLLO2-MOC and TRIPOLI4 [7].

4. MAIN RESULTS AND COMPARISONS

The figure 4 illustrates the power distribution obtained by the reference scheme i.e., the Monte-Carlo calculation. It may noticed that the hot assembly is located at the periphery of the core (E2 position), near the reflector. This comes essentially from the fuel management type where the fresh fuel assemblies are loaded at the periphery and the more depleted ones are reloaded at the centre (power level close to 0.5).

In term of reactivity, the difference between the Monte-Carlo model and the APOLLO2-MOC one is very low (< 300 pcm).
A very good agreement is obtained (cf. fig. 5) between the results given by the *Method of Characteristics* of the deterministic transport code APOLLO2 and the Monte-Carlo simulation since only two quarters of assembly show a discrepancy over 5%. These assemblies are located in the central part where the average power is low. A small power tilt between the center and the periphery (where the power is overestimated) is observed: the hot assembly power is underestimated of about 2%. This effect is due to the too rough 172-groups energy meshing, which is not really well adapted to treat accurately the large existing resonances for the intermediate mass isotopes without any treatment. The common self-

shielding APOLLO2 formalism isn't sufficient to compute Iron and Nickel cross sections which, in such a case where the diffusion plays a major role, overlap.
This hypothesis is verified by a calculation where the heavy reflector has been replaced by a water one (cf figure 6); the discrepancy is divided by 2 since a smaller power tilt is noticed and the majority of the discrepancies are less than three deviations.
These results indicate the importance of the self-shielding formalism for intermediate mass isotopes. So, the new developments for the treatment of mixing of isotopes and the definition of an adequate energy mesh could be the way to reduce the bias observed in the EPR core [10], [11].

The last comparisons concern the "industrial" 2 group diffusion route using a homogenous model with the deterministic CRONOS2 code.
In term of core reactivity, the discrepancies are rather low: -400 pcm compared to the TRIPOLI4 model and +100 pcm compared to the APOLLO2-MOC model.
For power distributions, it is noticeable that only one assembly shows a discrepancy over 5%, close to the reflector area (cf figure 7). This bias probably comes from the hypothesis which considers only the fundamental mode to compute all homogeneous cross sections with APOLLO2, even for peripheral assemblies, and from uncertainties in the description of the steel reflector equivalent cross sections. A radial tilt, lower than 2%, is observed, as well as a slight overestimation of fission rates in gadolinium assemblies. The hot assembly power is only underestimated by 2%, this range of discrepancy is completely sufficient for industrial applications.

5. CONCLUSION

The aim of this paper is to study an EPR core and its heavy reflector with the objective to quantify the methodological biases of different calculations, and the impact of the heavy reflector on the neutronic behaviour of the core. To reach these objectives, a reference heterogeneous pin by pin pointwise calculation has been compared with a pin by pin 172 group model using the method of characteristics and a homogenous 2-groups diffusion calculation.
The chosen core configuration is an Out/In fuel management for which there are 2 types of UO2 fuel assemblies and 5 batch burnups.
For the first time, a complete PWR core calculation with APOLLO2 and the Method of Characteristics have been performed. The results, compared with a reference Monte-Carlo calculation, using the TRIPOLI4 code, highlight a good agreement in term of reactivity and power distribution but some lacks have been found in the common self-shielding model and on the energy mesh for intermediate mass isotopes. A suggestion is to use the new self-shielding model, which takes into account the overlap of resonances, jointly with a more discretized energy meshing. This kind of model could be used as reference computation both for depletion and step zero cases, faster than with Monte-Carlo calculation, especially if a lot of output data are required by the user (the Monte-Carlo computation is costly if a lot of scores are required).
This work provides a complete set of calculation schemes for the neutronic evaluation of the European Pressurized water Reactor and stresses the quality and lacks of each of them, compared with a very accurate Monte-Carlo reference calculation, as well as it draws the ways of improving models.
2D core calculations, including reloading, are now available in APOLLO2, using the most recent developments in the method of Characteristics. Interesting ways to improve the here presented calculation deterministic scheme are:

- to reduce the number of energy groups for the the flux calculation, for example to about 20 groups,

- to keep a very accurate self-shielding computation, to be able to compute any fuel or poison type,
- to use the new accelerations method now available in APOLLO2.

6. References

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Fuel rod pitch	1,26 cm
Half water gap size	0,0734 cm
Fuel radius	0,407 cm
Clad radius	0,476 cm
Internal radius for guide-tube	0,564 cm
External radius for guide-tube	0,614 cm
Uox density	10.26 g/cm^3
Gd rods density	9.90 g/cm^3
Guide-tube density	6.51 g/cm^3
Clad density	6.51 g/cm^3
Gap dilution	0.92
Moderator density	0.70 g/cm^3

Table 1: Physical and technological parameters of fuel rods

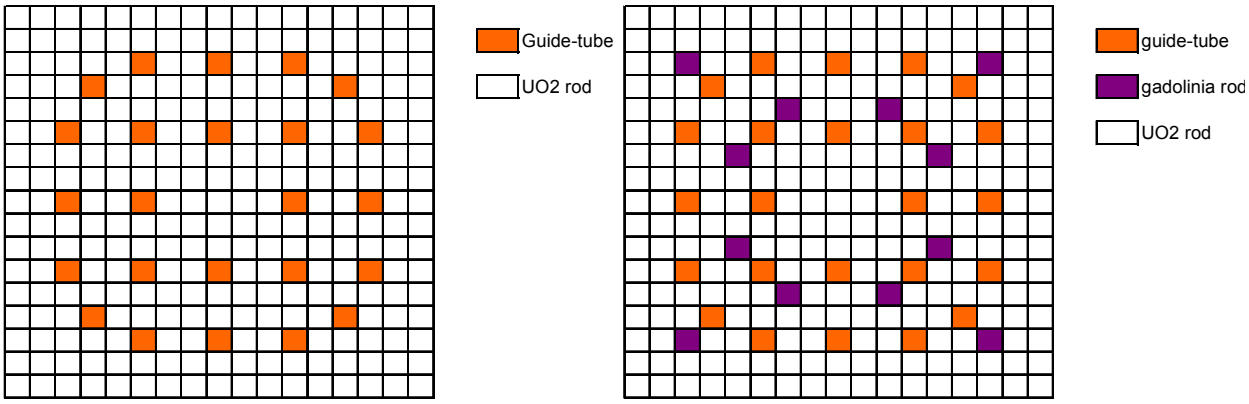

Figure 1: UO2 and UO2+gadolinium assemblies

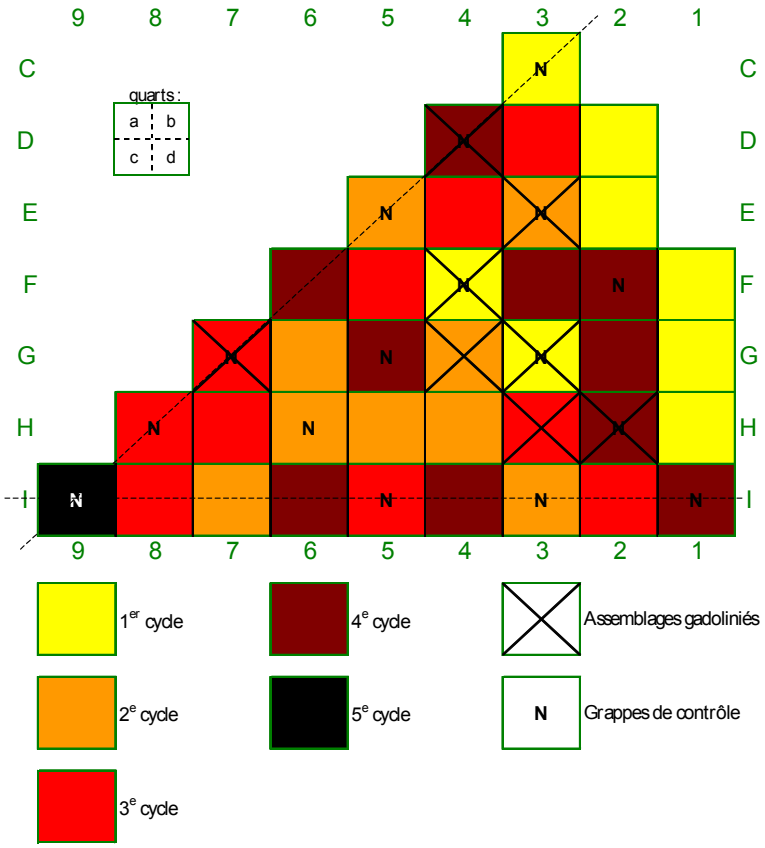

Figure 2 : OUT/IN Fuel management

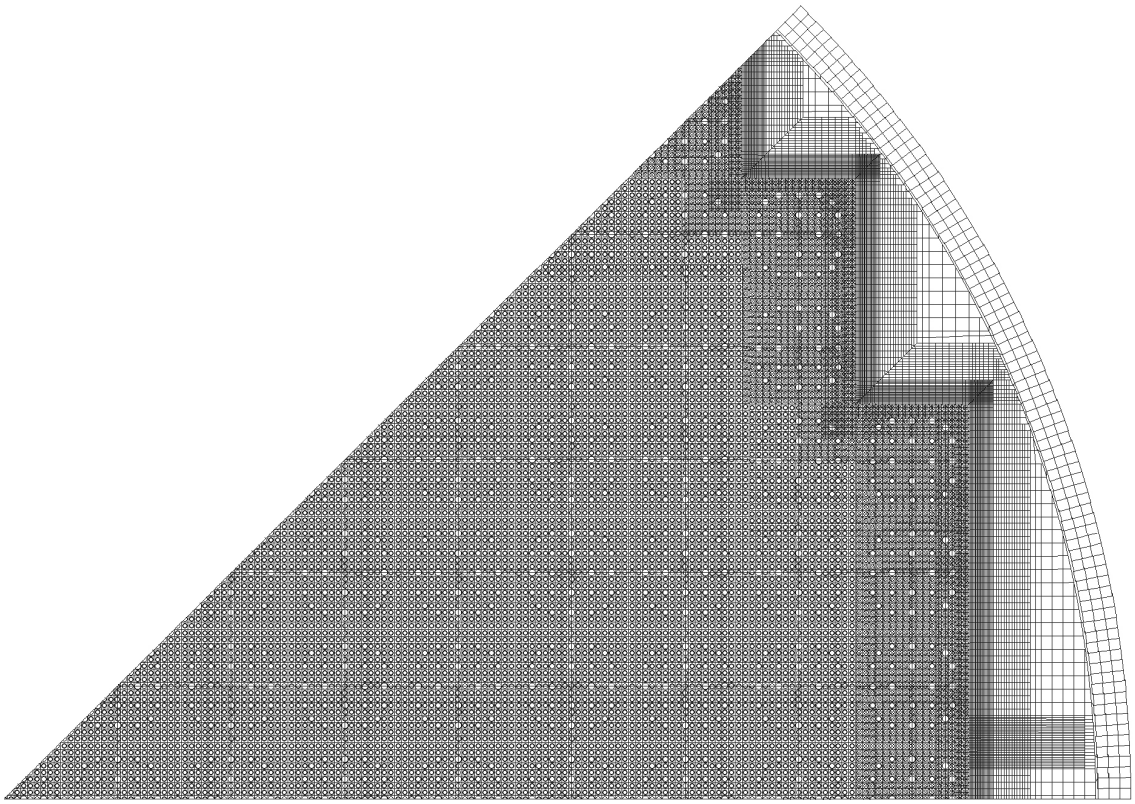

Figure 3: Calculation mesh used for the Method of Characteristics with APOLLO2 code

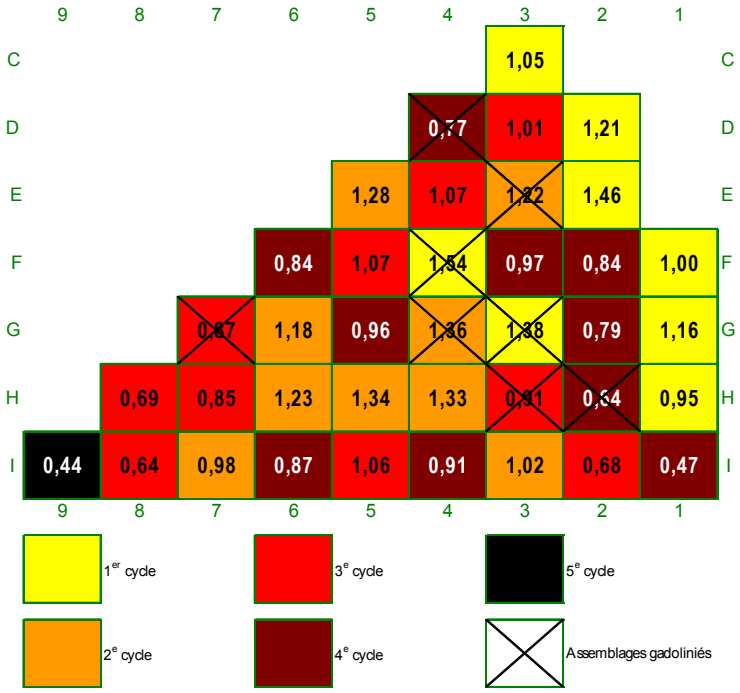

Figure 4: Assembly power map of EPR core obtained by TRIPOLI4

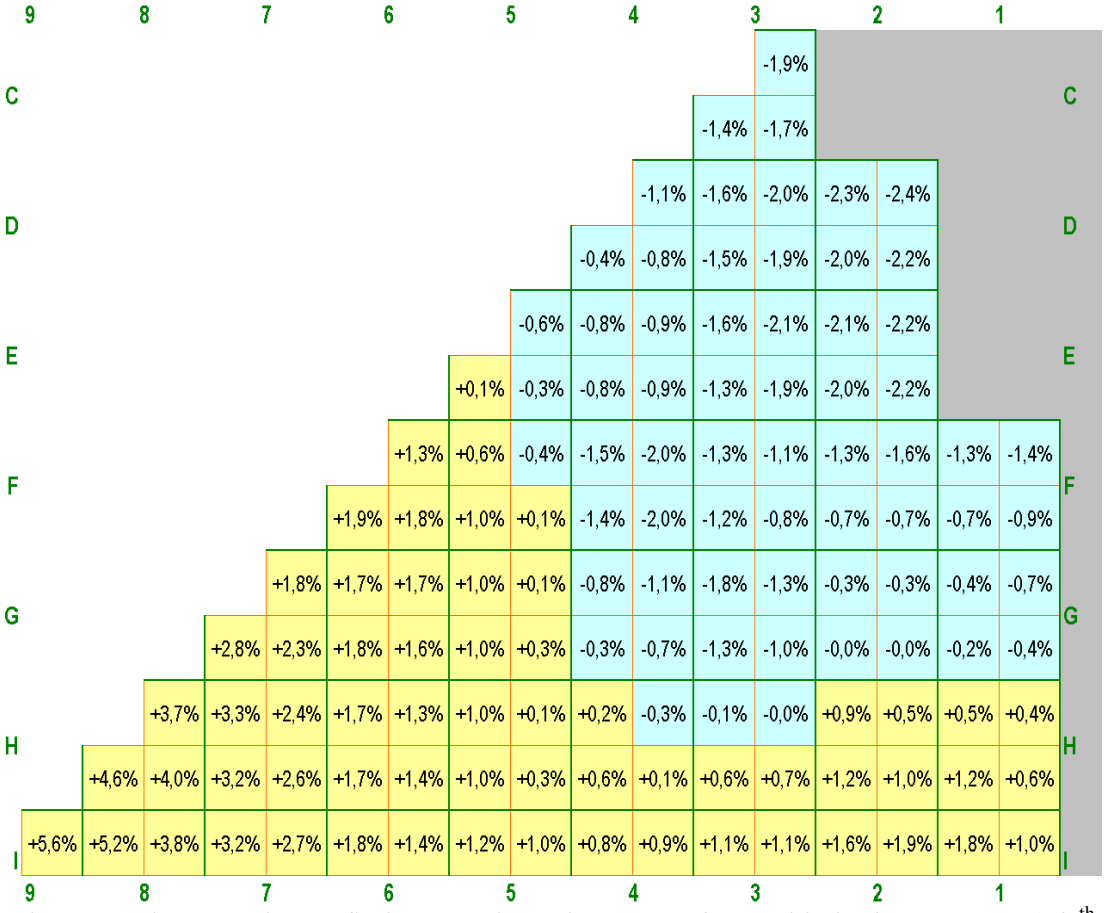

Figure 5: Discrepancies on fission rates in each quarter of assembly in the EPR core ($1/8^{th}$), calculated by the deterministic APOLLO2 code and by the Monte-Carlo code TRIPOLI4

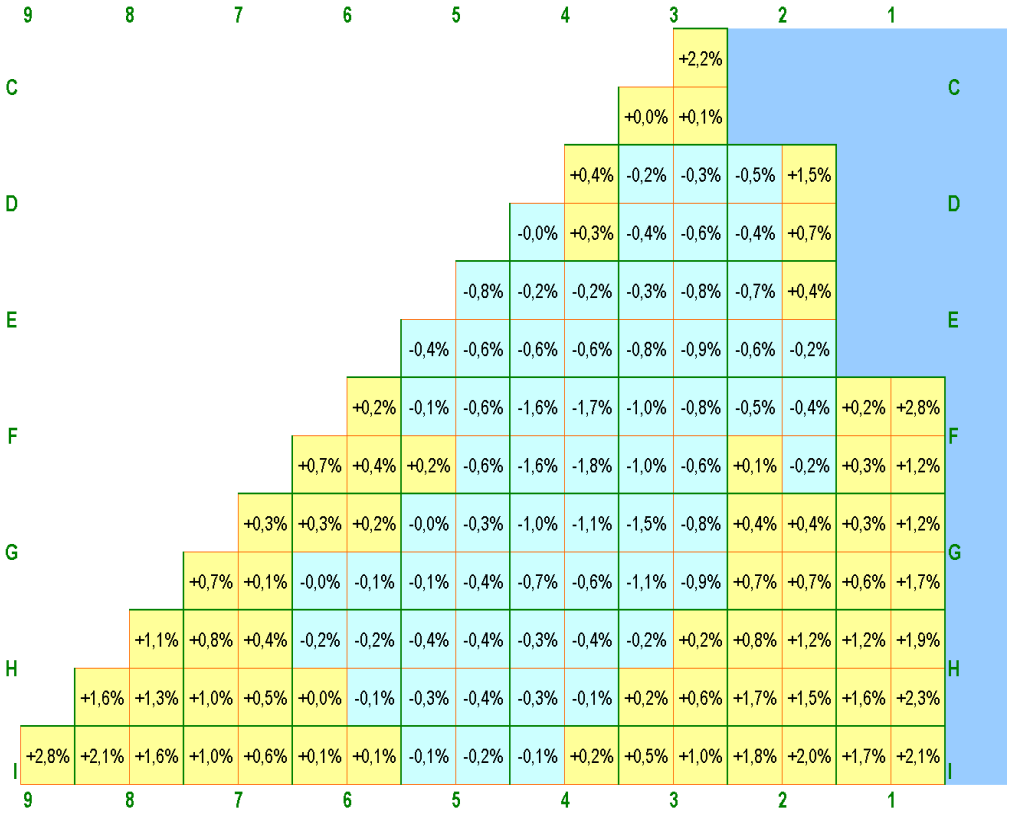

Figure 6: Discrepancies on fission rates in each quarter of assembly in EPR core with water reflector (1/8th), calculated by the deterministic APOLLO2 code and by the Monte-Carlo code TRIPOLI4

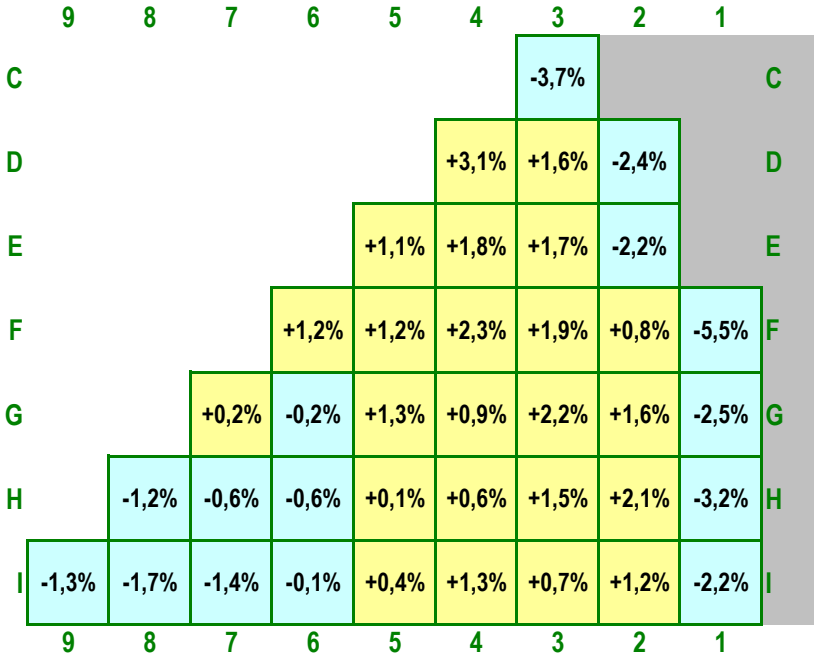

Figure 7: Discrepancies on assembly fission rates, calculated by the homogeneous CRONOS2 code and by the Monte-Carlo code TRIPOLI4