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NEUTRONIC MODELING FOR PEBBLE BED REACTORS

Maurice Grimod, Richard Sanchez and Frédéric Damian
CEA,
DEN, SACLAY, DM2S-SERMA,
F-91191 Gif-sur-Yvette, France.
maurice.grimod@cea.fr

ABSTRACT

In this paper we present a new iterative homogenization technique for pebble bed reactors. As opposed to previous methods, where a volume-averaged pebble is used for homogenization purposes, our technique includes the effect of local spectral differences in the homogenization process. The core is decomposed into several sub domains, called spectrum zones, each one of which comprises a stochastic distribution of pebbles with different burnups. In each zone the pebbles are grouped into burnup types and a collision probability description is derived by introducing a macro-stochastic model which describes the neutron exchanges between pebbles of different types and between pebbles and zone surfaces. The core is computed with a low-order operator, diffusion or transport, and, at each iteration, every spectrum zone is independently homogenized by solving a fixed k_{eff} source problem, where the k_{eff} and the entering currents are obtained from the previous core calculation. The convergence of the scheme has been verified and the results obtained for various configurations are satisfactory. The results of test calculations show that the use of an average pebble results in rather small errors in k_{eff} but discernible flux differences. However, it remains to analyze the effect on the final composition of the equilibrium core due to pebble recirculation.

Key Words: *Pebble Bed Reactor, homogenization, stochastic distribution, iterative core calculation*

1. INTRODUCTION

The Pebble Bed Reactor (PBR) is a High Temperature Gas-cooled Reactor, one of the six concepts studied in the Generation IV forum. The core, cylindrical or annular, contains a large number of graphite pebbles slowly flowing through it. Fuel TRISO particles are dispersed in a carbon matrix and imbedded in the interior part of the pebble. Furthermore, a multi-pass fuel management scheme and an online refueling procedure are adopted so that each pebble passes through the core a fixed number of times. Thus, during the equilibrium cycle, the core will be composed of a mixture of pebbles with different nuclide compositions, corresponding to the different burnups reached in their multi-pass history. Hence, the PBR comprises two levels of stochasticity: a) the stochastic dispersion of TRISO particles within each pebble and b) the stochastic distribution in the core of pebbles with different burnups.

The usual approach to calculate PBRs is to decompose the core into a set of sub domains (spectrum zones), defined from pebble-flow studies, to homogenize each of them via a transport calculation and to compute the homogenized core with a global diffusion calculation [1]. In this approach each spectrum zone contains several pebble types, with isotopic compositions representative of the average value of the burnups distribution of the pebbles re-circulated the

same number of times. Each pebble type has a multiplicity corresponding to the number of pebbles of that type.

Because the neutron mean free path in a PBR core is several times larger than the pebble diameter [2], the flux inside a pebble is strongly dependent on its surrounding. Therefore, the homogenization of the spectrum zones has to account for surface leakage, which must be evaluated from the core calculation, resulting thus in an iterative homogenization technique. This technique is akin to the interactive advanced techniques which are being investigated for LWRs [3].

Actually, the widest used code for industrial calculations of HTRs is V.S.O.P. [4]. In this suite of codes, the transport calculation of the spectrum zones is performed using two different codes, GAM and THERMOS, that treat two different energy ranges, the fast and epithermal one and the thermal one respectively. GAM performs a P_1 slowing-down calculation in an infinite homogeneous medium with a fixed source, generally with a U235 fission energy spectrum. Leakages are taken into account by a geometrical buckling, computed for each spectrum zone from the diffusion core calculation. THERMOS performs a collision probability calculation in a 1D spherical geometry, where the fuel region of the pebble is represented as a homogeneous material. Once again, a fixed source problem is solved, where the slowing-down source is given by the previous GAM calculation. Leakages are represented by an albedo on the surface of the pebble, which is also computed from the diffusion core calculation for each spectrum zone. They both deal with the two levels of stochasticity of the problem in the same way: a) the heterogeneity of the grains is treated separately and is taken into account by using selfshielding factors computed by other codes; b) the stochastic distribution of the pebbles with different burnup is not really treated, but a single pebble with an average material, obtained by volume averaging the isotopic atomic densities of the different pebble types contained in a zone, is used for calculation. As a consequence, a single neutron flux spectrum is used to homogenize and deplete all the pebble types contained in a spectrum zone.

In this work we present a new homogenization model for the spectrum zones, based on a macro-stochastic approach, which accounts for intra pebble neutron transport in the calculation of the flux and includes spectral effects in the homogenization. We have also developed an iterative scheme to couple the calculation of the spectrum zones with the actual core calculation, which is carried out with a low-order transport operator. The entering currents in each spectrum zone and the core k_{eff} are recovered from the core calculation.

The model and the iterative core calculation scheme are described in Section 2. A basic set of surface-to-surface probabilities is used in this model to construct the collision probabilities (CP) coefficients for a spectrum zone. In Section 3 we evaluate these probabilities from appropriate Monte Carlo calculations of a distribution of randomly packed pebbles inside an annular reactor. Finally, in Section 4 we present the results of our method applied to a simplified core configuration, making a comparison with a methodology based on the V.S.O.P. assumptions.

2. DESCRIPTION OF THE METHOD

Our work is an extension of an infinite-lattice homogenization technique [5], earlier implemented in the transport code APOLLO2 [6], to treat a finite spectrum zone by explicitly accounting for interactions between pebbles with different burnup histories and with pebbles from neighboring spectrum zones via interface currents.

We introduce a stochastic model to account for the random distribution of different burnups pebbles within a given spectrum zone, which represents the second level of stochasticity of the problem. Pebbles in a zone are grouped into a finite number of pebble types, characterized by average burnup and multiplicity, and pebble-pebble interactions are described by a CP formulation for one-dimensional pebbles which exchange neutrons among themselves and with a set of external surfaces (interfaces with neighboring spectrum zones or reflectors). The contribution of the coolant is also included. In our model, a set of pebble-pebble, pebble-surface and surface-surface geometric probabilities are introduced to write the closure relations between the average neutron currents entering and exiting each pebble type and each surface. For example, the pebble-pebble geometric probability $p^{\beta\alpha}$ is the probability for neutrons exiting uniformly and isotropically a pebble of type α to enter a pebble of type β without crossing any other pebble. All these probabilities obey reciprocity and conservation relations and can be derived from a basic set of surface-surface probabilities and from a statistical description of the pebbles distribution in the zone [5]. In our work we invoke a *uniform* model according to which the probability to find a pebble of a given type in a given location within the spectrum zone is proportional to the multiplicity of the type. Also, for safety analysis applications, a *clustering* model has been derived from the uniform model by artificially increasing the geometric self-probability for pebbles of a given type.

The final spectrum zone model is characterized by a set of equations giving the fluxes for each pebble type in terms of currents entering the surfaces, providing the potential for a full transport core calculation via interface currents, as well as the possibility to independently compute each zone from the currents entering it.

2.1. Iterative Core Calculation Scheme

Let D be the geometric domain of a spectrum zone which comprises pebbles of different types and the helium coolant. The flux in D obeys the exact transport source equation:

$$\begin{aligned}(\vec{\Omega}\cdot\vec{\nabla}+\Sigma)\psi &= H\psi+\frac{1}{\lambda_{core}}P\psi, \quad && x\in X,\\ \psi_{-} &= \psi_{-,core}, && x\in\Gamma_{-},\end{aligned} \tag{1}$$

where *H* and *P* are, respectively, the scattering and fission operators, λ_{core} is the core k_{eff}, $\psi_{-,core}$ is the angular flux entering the domain via its surface ∂D, X is the phase space associated to domain D and Γ_{-} the incoming boundary of X.

For each spectrum zone, the cross sections to be utilized in the full transport or diffusion coarse-group core computation are flux-weighted homogenized from a fine-group solution of Eq. (1). For the spectrum zone calculation we assume that the core entering angular flux is isotropic and piecewise uniform over a set of external surfaces, as defined by the contacts with the neighboring zones or reflectors. Therefore, the entering flux is represented by the values of the entering currents for each surface *k*, $\psi_-^g \rightarrow \{J_{-,k}^g\}$.We note that, because both the k_{eff} and the entering currents must be obtained from the coarse-group core computation, the calculation scheme is necessarily iterative. Finally, the value of $J_{-,k}^g$ is obtained by preserving the corresponding $(J_{-,k}^G)_{core}$ core value:

$$(J_{-,k}^g)^{(n)} = \left[\frac{(J_{+,k}^g)_{neighbor}}{\sum_{g\in G}(J_{+,k}^g)_{neighbor}} (J_{-,k}^G)_{core} \right]^{(n-1)}, \qquad (2)$$

where the quantities on the right hand side are obtained from the previous iteration, *g* is the fine group index and *G* is the coarse group index.

This interactive core homogenization scheme is illustrated in Fig. 1. The iterations are initialized from a critical-buckling infinite-lattice calculation for each spectrum zone.

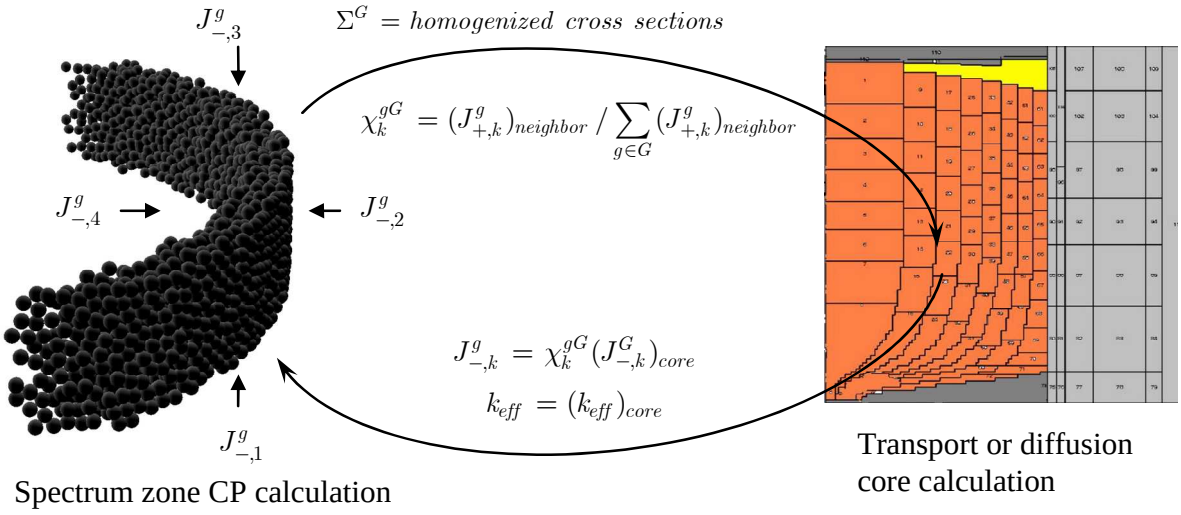

Figure 1. Scheme for iterative core calculation.

Note that the spectral shape factor χ_k^{gG} for the entering current is obtained from the fine-group transport current $(J_{+,k}^g)_{neighbor}$ exiting the corresponding neighboring spectrum zone or the reflector. Each iteration begins with the fine-group transport calculations for the spectrum zones

and ends with a full coarse-group core calculation. The latter is converged as usual on the fission integral shape and the k_{eff}. The convergence criteria for the iterative core calculation is achieved when the maximum relative difference between two consecutive iterations on the fission integrals, the core currents entering the spectrum zones and the homogenized total cross sections, as well as the absolute difference in the k_{eff}, are bellow user's prescribed values.

Finally, a transport description of the graphite reflectors is needed to obtain the homogenized coarse-group cross sections and to determine the current spectral shape factor for the spectrum zones having surfaces in contact with the reflectors. In our calculation scheme, this was done by performing axial and radial 1D fine-group transport calculations of the reactor, using for the core the cross sections obtained by homogenizing the spectrum zones with the initial infinite-lattice calculations.

2.2. CP Treatment for the Spectrum Zone

To formulate a numerical approximation for Eq. (1) we consider each pebble type as a 1D spherical geometry and cast the corresponding transport equations into a collision probability formulation:

$$\begin{aligned} V_i\vec{\Phi}_i &= C_i\vec{F}_i + \vec{I}_i J_{-,i}, \\ J_{+,i} &= \vec{E}_i\vec{F}_i + T_i J_{-,i}, \end{aligned} \tag{3}$$

where we have omitted the group index, *i* denotes the pebble type, C_i, $\vec{I}_i$, $\vec{E}_i$ and T_i are the CP coefficients, V_i contains the pebble region volumes, $\vec{\Phi}_i$ is the vector of region-averaged fluxes, $\vec{F}_i = \Sigma_{si}\vec{\Phi}_i + \vec{Q}_i$ and $\vec{Q}_i$ accounts for fission and external transfers. Finally, $J_{\pm,i}$ is the total current exiting (+) or entering (–) the overall surface of the pebbles of type *i*.

The first equation in (3) allows the region fluxes to be computed within any pebble type in terms of the total current entering the pebbles of that type. This current is derived from the currents exiting the pebbles and those entering the surfaces of the spectrum zone accounting for the absorption and diffusion of the Helium. In Ref. [5] this effects were accounted for by assuming that the chord lengths within the Helium followed a Markovian distribution [7]. This approximation led to the equations [5]:

$$\vec{J}_- = t_{He}(p^{p,b}\vec{J}_-^{bd} + p^{p,p}\vec{J}_+ + \vec{a}^p f_p V_{He} F_{He}) \tag{4}$$

$$\vec{J}_+^{bd} = t_{He}(p^{b,b}\vec{J}_-^{bd} + p^{b,p}\vec{J}_+ + \vec{a}^b f_b V_{He} F_{He}) \tag{5}$$

for the currents entering the pebbles and exiting the external surfaces, and

$$V_{He}\Phi_{He} = \lambda_{He} t_{He} \left(\sum_k J^{bd}_{-,k} + \sum_i J_{+,i} + V_{He} F_{He} \right) \tag{6}$$

for the averaged flux in the Helium coolant, where

$$t_{He} = < e^{-\Sigma_{He} l} > = \frac{1}{1 + \lambda_{He}\Sigma_{He}}, \tag{7}$$

$\vec{J}_{\pm} = \{J_{\pm,i}\}$, $\vec{J}^{bd}_{\pm} = \{J^{bd}_{\pm,k}\}$ are the currents exchanged through the zone surfaces, V_{He}, λ_{He} and Σ_{He} are, respectively, the total volume, the mean chord length and the total cross section for the coolant, $p^{p,p}$, $p^{p,b}$, $p^{b,p}$ and $p^{b,b}$ are pebble-to-pebble, surface-to-pebble, pebble-to-surface and surface-to-surface geometrical probabilities, $\vec{a}^{p}$ and $\vec{a}^{b}$ are the relative areas of each pebble type and surface, respectively, and f_p and f_b are the fraction of the overall pebbles area and of the zone surfaces over the total area of interaction.
Finally, for computational efficiency we algebraically eliminate the currents entering and leaving the pebbles, $\vec{J}_{-}$ and $\vec{J}_{+}$, and cast the equations in the CP form

$$V\vec{\Phi} = C\vec{F} + I\vec{J}^{bd}_{-}, \tag{8}$$

where $\vec{\Phi}$ contains all the region-averaged fluxes in all pebble types plus Φ_{He}.

As a final comment, we point out that the stochastic distribution of the TRISO particles in a pebble is treated with the double-heterogeneity method and it is thus incorporated in the CP coefficients [6].

3. ANALYSIS OF SURFACE - SURFACE PROBABILITIES

The surface-surface probability $p^{k'k}$ for a spectrum zone is the probability for a neutron entering uniformly and isotropically surface k to leave the zone via surface k' without crossing any pebble.
As it is shown in Ref. 5, once the $\left\{p^{k'k}\right\}$ are known and a distribution model for the pebbles is assumed (the *uniform* one in our case), all the other geometrical probabilities needed to compute the CP coefficients for a zone are deduced.

However, in our implementation surface-surface probabilities for every spectrum zone in the core have to be provided as external data, so it is necessary to evaluate them independently. The $p^{k'k}$ depend on the core type (cylindrical or annular) and the size, shape and position of the spectrum zone in the core. The oscillations of the packing fraction near the reflector influence neutron streaming. In our model, radial and axial streaming effects, which occur in the zones in

contact with the reflector, can be easily accounted for by adopting appropriate surface-surface probabilities. Indeed, the presence of a wall forces the pebbles to rearrange close to it, resulting in a locally less dense packed bed and an increase of the $p^{k'k}$.

A study for a pebble bed randomly packed in an annular core was carried out with the Monte Carlo code TRIPOLI4 [8] to evaluate the values of the $p^{k'k}$ in a typical bed, and observe the influence of the external and internal reflectors on the surface-surface probabilities. The random pebble distribution has been taken from another study which simulated a 3D packing of pebbles in an annulus of 100 cm internal radius, 186 cm external radius and 10 m height [9]. The pebbles have a diameter of 6 cm and the bed is characterized by a packing fraction of 0.61, a typical value for PBRs. Zones of various sizes were positioned in different parts of the core and the surface-surface probabilities were obtained by applying a uniform and isotropic neutron source on a boundary surface and scoring only the neutrons crossing the zone without entering any pebble. The schematics of the simulated geometry is shown in Fig. 2.

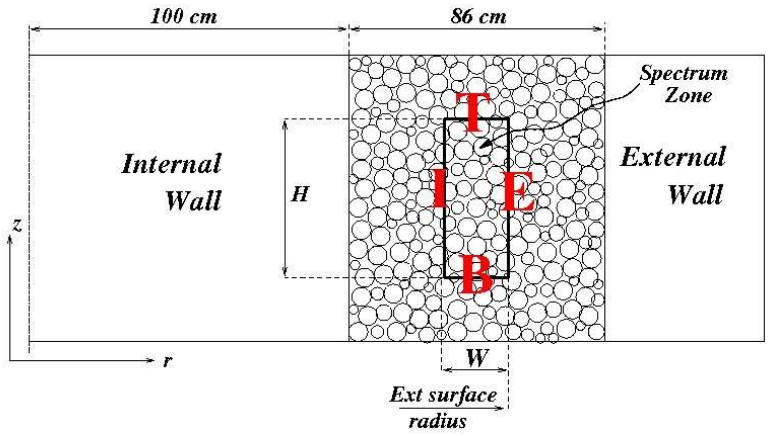

Figure 2. Schematics of the geometry used to analyze the $p^{k'k}$ of a spectrum zone

The various zones defined for the analysis have the shape of an annulus with rectangular cross section. It is thus possible to distinguish an External, an Internal, a Top and a Bottom surfaces. For example, p^{BT} is the top to bottom probability.

Notice that each zone requires a set of 16 $p^{k'k}$, but these probabilities must satisfy the reciprocity relation $p^{k'k}A_k = p^{kk'}A_{k'}$ and the form and symmetries of the zone require that $p^{TT} = p^{BB} = p^{II} = 0$, $p^{TE} = p^{BE}$ and $p^{TI} = p^{BI}$, which leaves only five probabilities to be determined.

The results of the analysis are shown in Fig. 3 to 7. In these figures $p^{k'k}$ is indicated as $k \to k'$ and H, W and $\mathbf{R_E}$ denote the zone's height, width and the External surface radius, respectively (see Fig; 2).

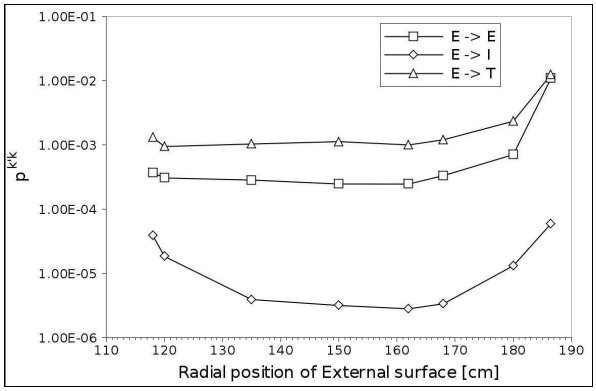

Figure 3. $p^{k'k}$ for H = 50 cm and W = 18 cm versus external radius R_E.

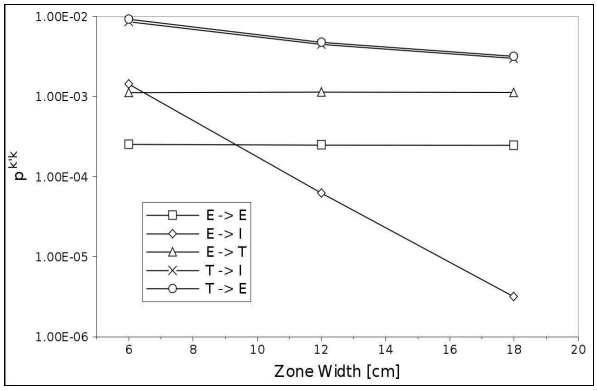

Figure 4. $p^{k'k}$ for H = 50 cm and R_E = 150 cm versus region width W.

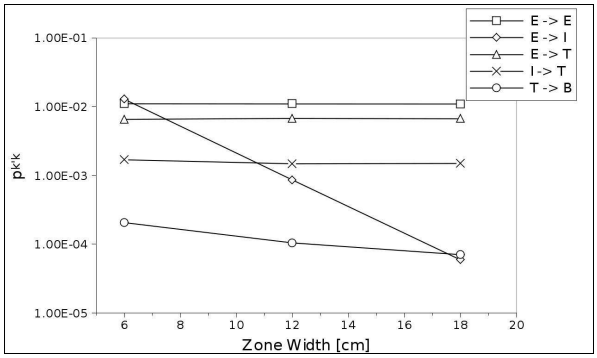

Figure 5. $p^{k'k}$ for H = 50 cm and R_E = 186 cm (external surface on the reflector wall) versus region width W.

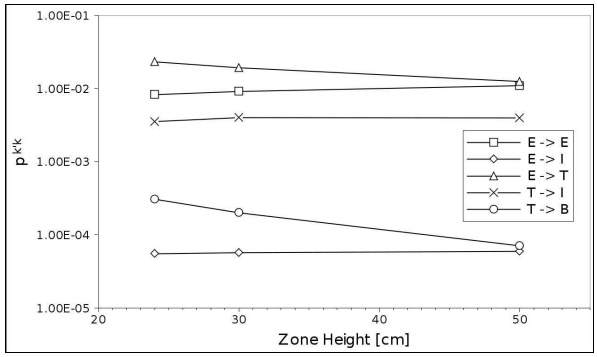

Figure 6. $p^{k'k}$ for W = 18 cm and R_E = 186 cm (external surface on the reflector wall) versus zone height H.

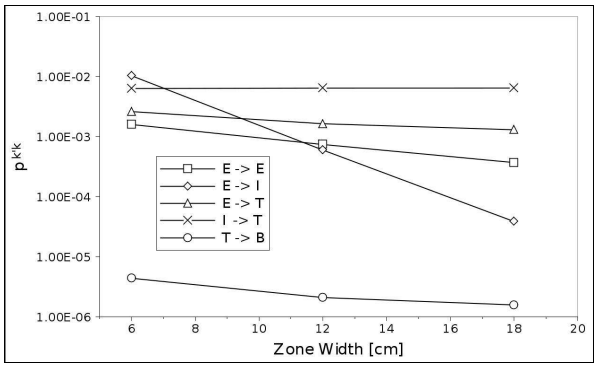

Figure 7. $p^{k'k}$ for H = 50 cm and R_I = 100 cm (internal surface on the reflector wall) versus region width W.

From Fig. 3 it is possible to evaluate the increase of the $p^{k'k}$ when the zone is close to the reflectors, starting at about 3 pebble diameters from the wall. In the internal part of the core, the

values are almost constant. In Fig. 4, the zone has a fixed height and a variable width, with the external surface in a fix position at a radius r = 150 cm. We notice $p^{BT} \simeq 0$ when the zone is not close to a reflector (also when the height is smaller than 50 cm). Moreover, we observe that $p^{IT} \approx p^{ET}$ even if the internal surface has a smaller area than the external one, and that p^{TE} does not increase when the width of the zone, and so the top area, increases. This means that the larger contribution to $p^{k'k}$ between two perpendicular surfaces mainly occur in the corner region. From Figs. 5 and 7 we notice that, when the zone is in contact with the reflector, p^{IE} is one order of magnitude greater than in Fig. 4 and that p^{BT} is not negligible, showing the locally enhanced radial and axial neutron streaming close to the wall. From Fig. 6 we observe that p^{BT} varies slightly with the zone height and that p^{TE} increases when the height decreases, due to the fact that a larger fraction of the external surface is in the corner region with the top surface.

This analysis gives an evaluation on the values of the $p^{k'k}$, depending on the size and position in the core of the spectrum zone, which can be used to establish the core modeling. These values are small, but the sensitivity of the core calculation to the values of the surface-to-surface probabilities needs to be investigated. However, this analysis is made in a particular core configuration, and so it does not include all the aspects that would still have to be studied for the modeling a real configuration.

4. TEST CALCULATION

A calculation exercise was performed with the APOLLO2 code to evaluate the model described in Section 2. An annular core, with 1 m internal radius, 1.54 m external radius and 1.50 m height, surrounded by upper and lower reflectors of 1 m thick and by an external reflector of 0.70 m thick, contains 6 different pebble types with different burnups, as described in Table I. The composition of the pebbles was obtained by depleting a typical PBR fuel pebble with reflective boundary conditions up to several burnup steps. The core is subdivided in 9 spectrum zones of width 18 cm and height 50 cm each containing the 6 different pebble types with a packing fraction of 0.61. The proportions of the different pebbles in the spectrum zones are also given in Table I and a schematics of the reactor is shown in Fig. 8. Spectrum zones 1, 2 and 3 contain 3324 pebbles each, while spectrum zones 4, 5 and 6 contain 3873, and spectrum zones 7, 8 and 9 contain 4422; for a total of 34857 pebbles in the reactor. All the materials are at a temperature of 20 °C.

The transport zone calculations were done with a 172-group library (JEFF2.2), whereas the RZ core calculations were done with discrete ordinates diamond differencing and 8 broad-energy groups. Also, radial and axial 1D S_N calculations were carried out to homogenize the reflectors and to compute the spectra χ_k^{gG} of the currents exiting them (definition given in Fig. 1).

The convergence criteria for the maximum relative differences from the previous iteration, were fixed at 10^{-4} for the fission integrals and for the entering currents per group and per boundary

surface, and at 10^{-5} for the homogenized total cross sections and for the k_{eff} (for this last parameter the criterium is applied to the absolute difference).
The core calculation scheme converged after 14 spectrum zones – core iterations with k_{eff} = 0.99927.

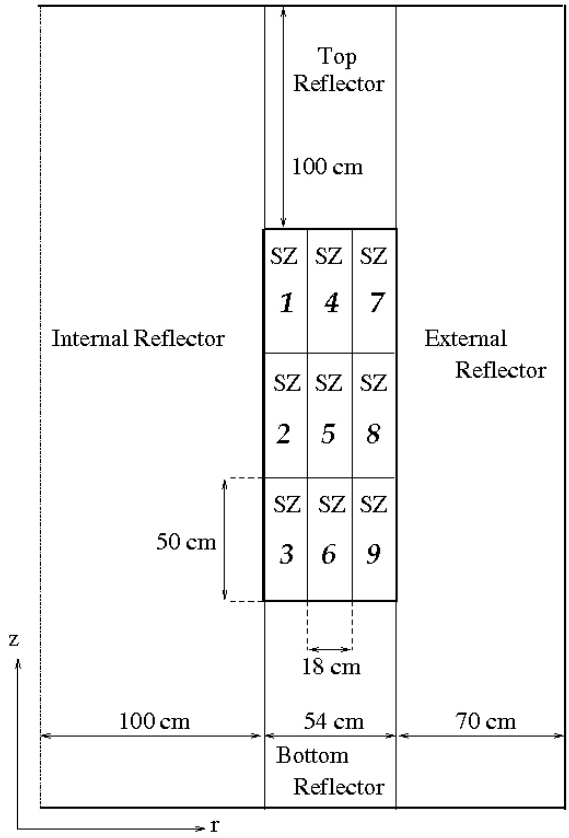

Figure 8. Schematics of the simulated reactor

Table I: Burnup of pebble types in the core and fractions in the spectrum zones.

Pebble type	Burnup [MWd/t]	Fraction in spectrum zones		
		1, 4, 7	2, 5, 8	3, 6, 9
A	0	0.25	1/ 6	0.10
B	15000	0.20	1/6	0.11
C	30000	0.18	1/6	0.16
D	50000	0.16	1/6	0.18
E	75000	0.11	1/6	0.20
F	95000	0.10	1/6	0.25

The convergence process of the various parameters is gathered in Fig. 9. This figure illustrates the convergence of the scheme, which depends also on the convergence criteria adopted for the collision probabilities calculations of the spectrum zones and for the S_N calculation of the core.

To illustrate the spectral effects, Fig. 10 shows the spectra of the currents entering spectrum zone (SZ) number 8, each one of which is obtained by using the corresponding χ_k^{gG} shape factor to expand in 172 groups the broad-group current issued from the core calculation. The presence of the external reflector is clearly highlighted by the highly thermalized angular flux entering the corresponding boundary. One can observe that the spectrum of the current entering from SZ5, which is located in the centre of the core, is harder than the ones from SZ7 and SZ9, which are close to the reflector.

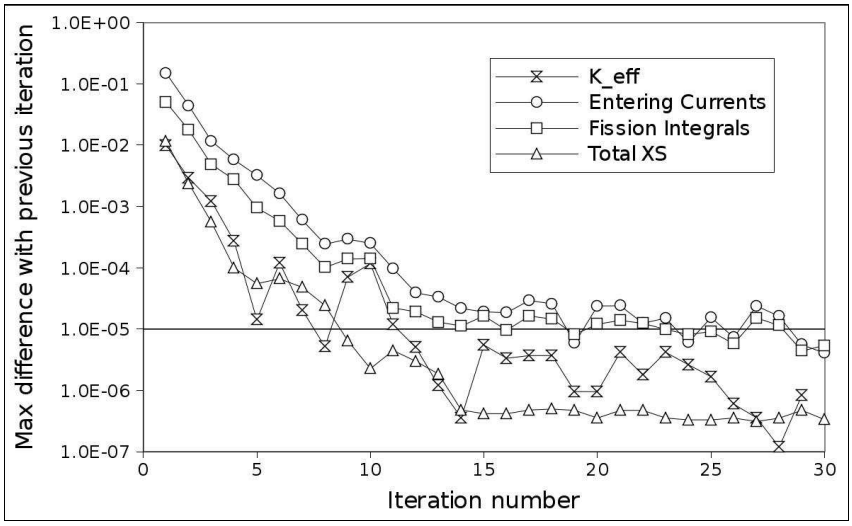

Figure 9. Convergence behavior of the core calculation.

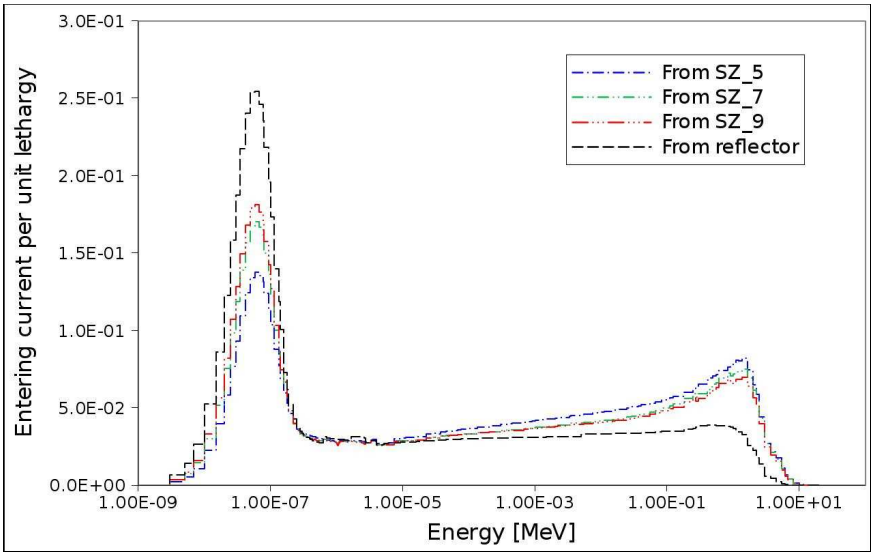

Figure 10. Spectra of currents entering Spectrum Zone 8.

For a second calculation we then wanted to simulate the V.S.O.P. methodology, where the second level of stochasticity of the problem is treated by using a pebble with a volume-averaged material, as explained in Section 1, and to compare it with our method.

We so compute the same reactor but with the spectrum zones containing a single pebble type. This last one owns the isotopic composition of the TRISO fuel kernels equal to the average composition of the different pebble types contained in the zone, weighted on the number of pebbles reported in Table I. The fluxes in the spectrum zone regions are still computed through Eq. 8. The geometric probabilities, used to construct the CP coefficients for a spectrum zone, are

deduced starting from the same set of surface-to-surface probabilities $p^{k'k}$ as for the previous calculation. The selfshielding is also performed using this equation in reflected conditions, and so still taking into account both the intra-pebble and the extra-pebble contributions to the first-flight collision probability for a neutron generated inside a fuel kernel to collide in another kernel, of the same pebble or of a neighboring one.

We have compared the spectra in the fuel kernels of the different pebble types in a zone with the one computed in the kernels of the corresponding average composition pebble. The relative differences between the spectra are shown in Fig. 11.

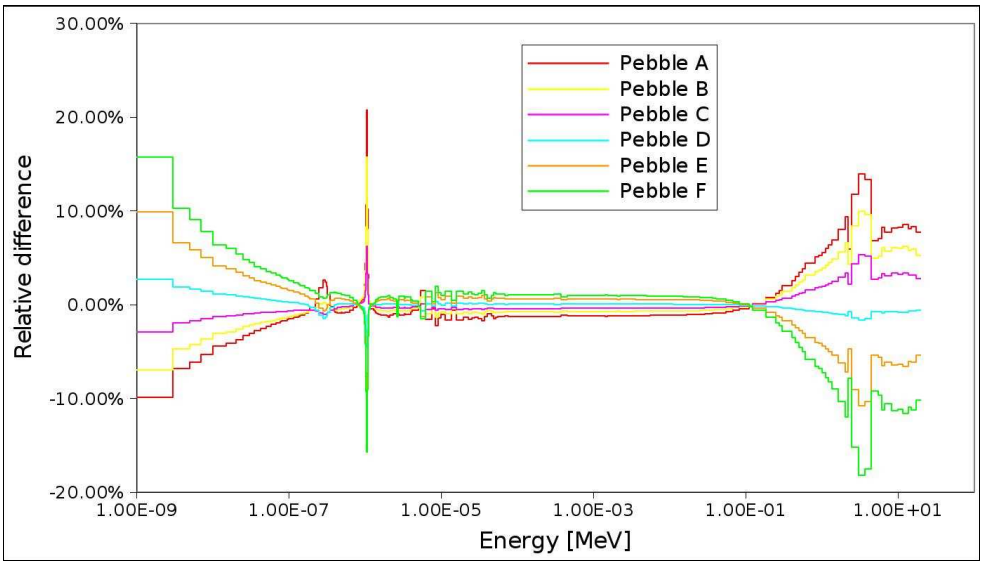

Figure 11. Differences in the kernels spectra relative to the average pebble

The strong effect on the spectra of the resonance peak of Pu240 at 1.06 eV is highlighted. For pebble A, a smaller influence of Pu239 and Pu241 at about 0.3 eV can be noticed. The magnitude of the differences is similar to those observed in others independent previous analyses [10, 11]. In one of them, the spectral differences between the fluxes in the fuel kernels of different burnup pebbles and of an average composition one were analyzed by a Monte Carlo simulation.
When an average pebble is used for the flux calculation, the computed k_{eff} is 1.00013, only 86 pcm higher than the one obtained in the first calculation. The maximum relative difference between the two cases in the total 8-group homogenized cross sections of the spectrum zones is 0.12%, in the group ranging from 0.625 to 1.67 eV, where the Pu240 resonance peak is located. The difference is rather small, and this is due to an error compensation which occurs when the 6 pebbles are averaged in a single composition pebble, as the differences in the spectra are symmetrically distributed. Also the maximum relative difference in the broad-group entering currents per boundary surface in the spectrum zones is small and does not exceed 0.57%.
The use of the proper spectra in the different pebbles will probably have a greater effect when depletion calculation will be considered.

5. CONCLUSIONS AND FUTURE WORKS

In this paper we illustrated the iterative homogenization technique developed in APOLLO2 for pebble bed reactors. Compared to the previous methods used in pebble bed simulations, this method can directly deal with the stochastic distribution of pebbles of different burnups in the core, taking into account the neutron flux spectral differences in the various pebbles. Moreover, it can easily treat the increased neutron streaming through the pebble bed close to the reflector by the use of proper $p^{k'k}$. This effect was studied for a particular annular configuration: a more extensive study should be done to obtain general knowledge on the values of surface-surface probabilities in various geometries. In the illustrated exercise, it appears that the use of an average pebble in the spectrum zones, rather than a multi-pebble geometry, doesn't influence in a significant manner the results on the k_{eff}, on the homogenized cross sections and on the entering currents per spectrum zone. The use of an average material for the fuel kernels is so acceptable and time saving for the calculation of a core where the pebbles have a given composition.

However, considering the proper spectra in the pebbles characterized by different burnup evidence discernible flux differences in the fuel kernels and this will certainly impacts the depletion calculation. This means that, due to the recirculation of the pebbles in the reactor, the composition of the equilibrium core should result quite different between the two methodologies.

In our future work, we will study the influence of the spectral differences in the pebbles on depletion calculations. Moreover, we will introduce diffusion as the low-order solution of the core. Finally, a comparison with a Monte Carlo simulation will be made to have a reference calculation.

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