HTR-N

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Calculational Results for the HTR-10 Benchmark Problems

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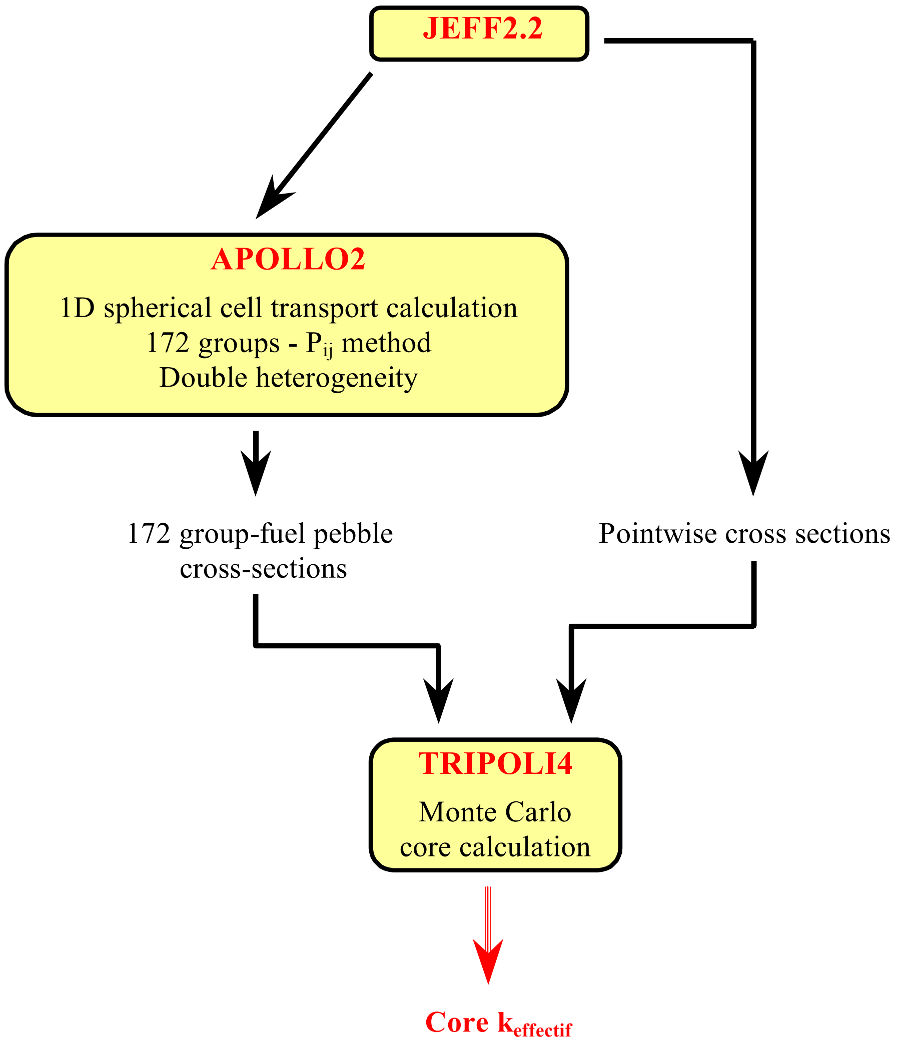
1GENERAL ANALYSIS METHOD AND MODEL DESCRIPTION

1.1. CODES AND CALCULATION SCHEME

In the following HTR-10 calculations, the French reactor physics code system SAPHYR has been used. SAPHYR gathers several codes developed at CEA like APOLLO2 [1] (transport) based on a database produced with THEMIS/NJOY, CRONOS2 (diffusion-transport), FLICA4 (3D- thermal hydraulics), ..., which are interconnected. Besides, the Monte-Carlo code TRIPOLI4 [2] has also been used throughout the study.

All the HTR-10 problems proposed in reference [3] have been treated considering a calculation scheme based on a Transport – Monte-Carlo method. Figure 1 illustrates the general procedure. The standard 172-group or point-wise cross sections library issued mainly from JEF-2.2 are used for the calculations.

FIG. 1 Description of the Transport – Monte-Carlo calculation scheme



1.2. FUEL PEBBLE CALCULATION (APOLLO2)

Knowing that the stochastic geometries calculations (coated fuel particles - CFP - randomly distributed in the inner zone of the fuel pebble) are not available in the Monte-Carlo code TRIPOLI4, a 1D-cell calculation has been performed as a first step (Figure 2). It takes into account a precise spherical description of the particles with their coatings, which themselves fill the spherical fuel zone of the pebble. The self-shielding of the uranium isotopes is calculated during this calculation step. A collision probability method is used to solve the transport equation with 172 energy groups. The critical buckling search allows taking into account the neutron leakage by the addition of an homogeneous leakage term in the form of $DB^2\Phi$. The extra region of the spherical cell is representative of the helium coolant plus the moderator pebbles (dummy balls) loaded into the core with the fuel pebbles. The volume of the extra-region has been calculated by considering a volumetric filling fraction of pebbles (fuel and dummy balls) of 0.61 in the core and a 57:43 fuel-to-moderator pebble percent ratio.

FIG. 2 Spherical Fuel Pebble Model in APOLLO2

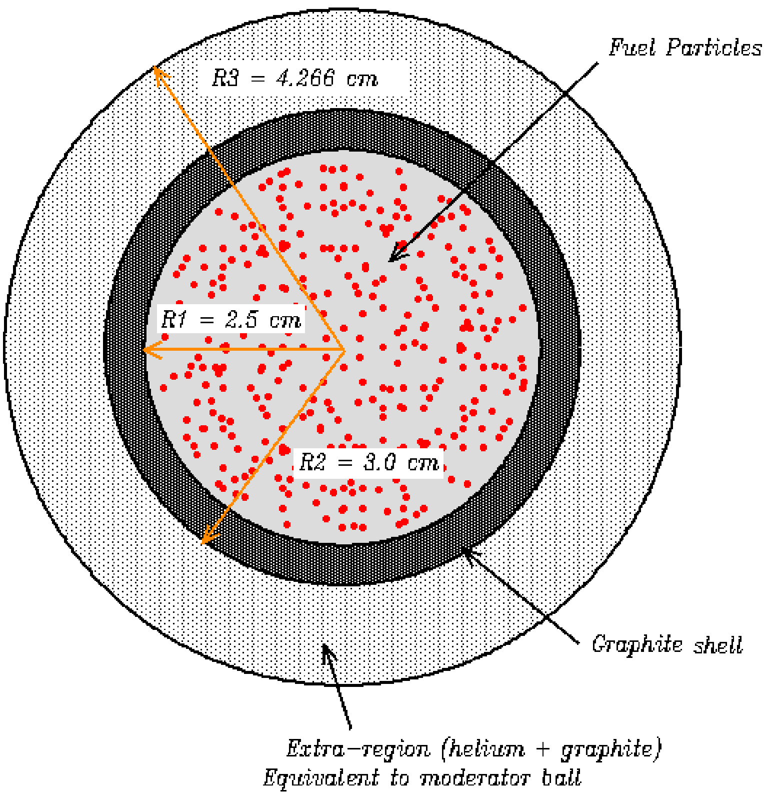


FIG. 3 Average neutron spectrum in fuel kernel and in fuel pebble surrounded by extra-region

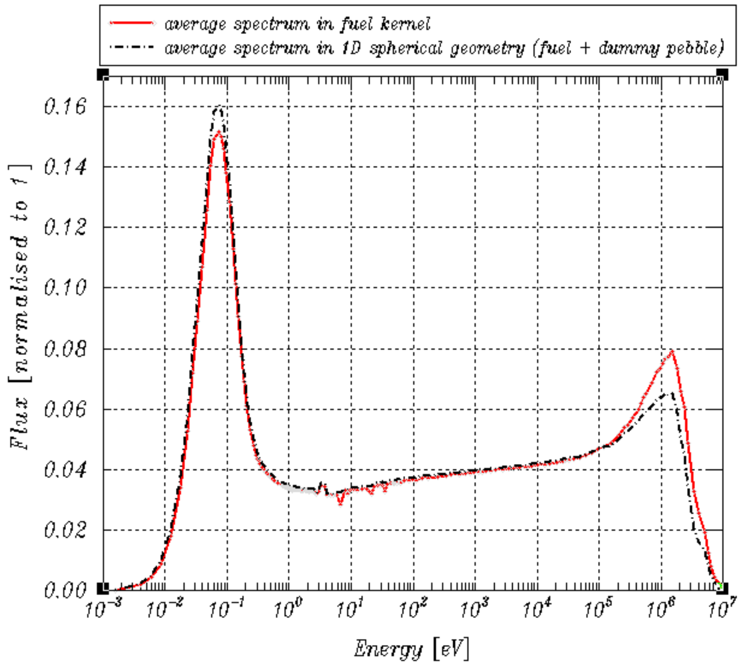


TABLE. 1 1D spherical – Transport calculation results in APOLLO2

	$k_{infinity}$	M^2 [cm^2]
Enrichment of U235 (weight) 17%	1.71926	1298.0

This first stage provides **172-group fuel region averaged cross sections** for Monte-Carlo core calculations (TRIPOLI4). The fuel homogenisation is performed with respect to the pebble bed description in the Monte-Carlo code TRIPOLI4 (see section 1.3). Indeed, for this benchmark, two types of pebble bed modelling have been analysed. In the first one, the core calculations have been performed considering an homogenised pebble bed (mixture of fuel, moderator pebbles and coolant). In the second one, each pebble has been modelled in the core. For this last case, the fuel pebble calculation in APOLLO2 provided the homogenized cross sections for the fuel pebble inner zone (radius = 2.5 cm).

Therefore, in the core calculations performed by TRIPOLI4, pointwise cross sections are used everywhere in the core except in the fuel pebble region where the multigroup cross sections have been generated with APOLLO2.

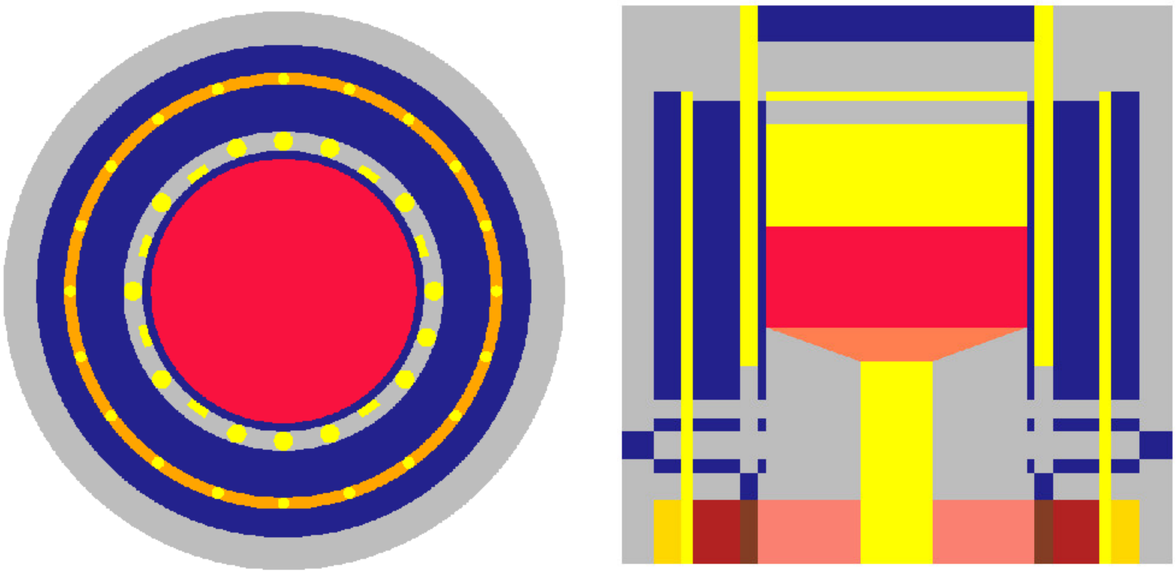
1.3. MONTE-CARLO CORE CALCULATION (TRIPOLI4)

1.3.1 Pebble bed modelling

Two sets of calculations have been performed on the core geometry. In both cases, all the core components are explicitly modelled (coolant and control rod channels…). The major difference concerns the pebble bed modelling (fuel and dummy balls modelling).

In the first modelling, the pebble bed is represented with an homogeneous medium as shown on Figure 4. This homogeneous medium is a mixture of fuel, moderator pebbles and coolant. The equivalent pebble bed cross sections are homogeneous cross sections issued from APOLLO2 calculations (homogenisation of the 1D-spherical geometry). This modelling will be called **"Simplified Pebble Bed modelling"**.

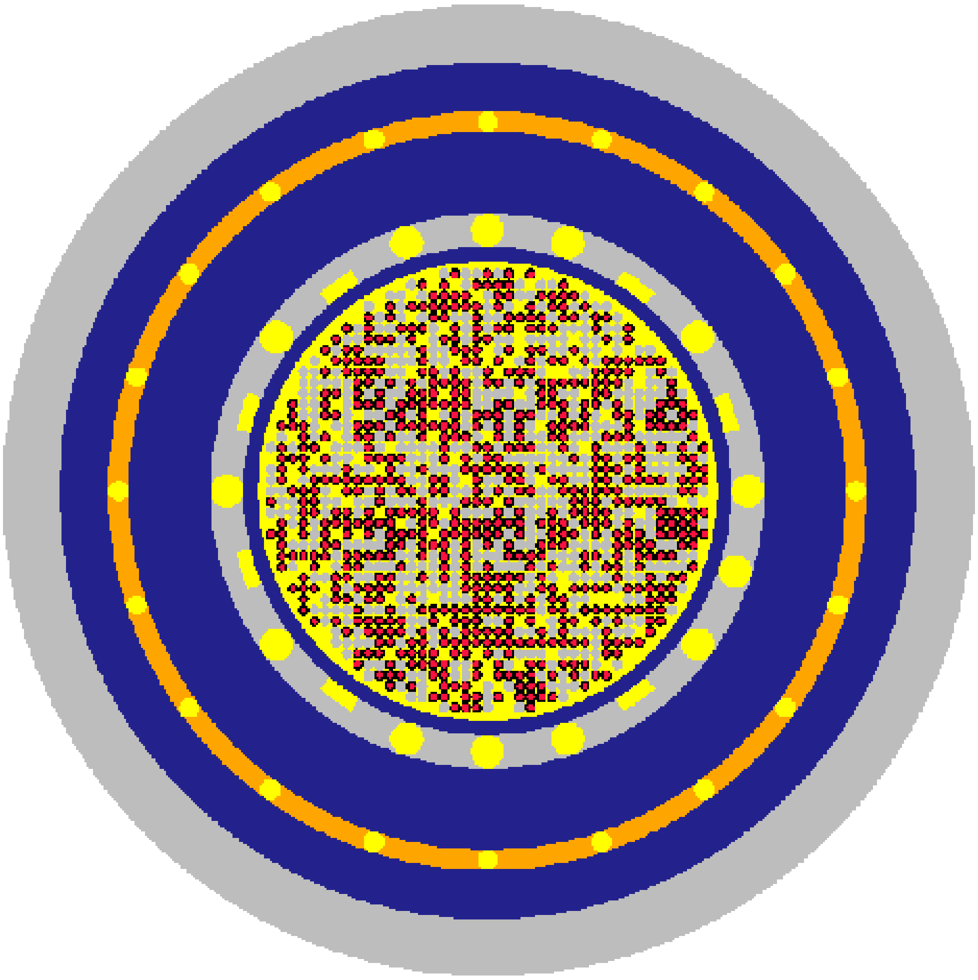
FIG. 4 Core modelling in Monte-Carlo code TRIPOLI4 ("Simplified PB modelling")



In the second set of calculations, all the pebbles (fuel and moderator pebbles) loaded into the core have been described explicitly. Considering a Cubic-Face-Center lattice (theoretical filling fraction of 74%), the fuel and dummy pebbles have been randomly placed at lattice nodes to achieve an average filling fraction of 61% (Figure 5).

Besides, the specification of a 57:43 fuel-to-moderator pebble percent ratio for the initial HTR-10 core loading has been respected. For the calculations, the homogenised cross-sections for the fuel pebble inner-zone have been evaluated by APOLLO2. For the moderator pebble and the fuel pebble outer region, pointwise cross sections are used. This modelling will be called **"Improved Pebble Bed modelling"**.

FIG. 5 Core modelling in Monte-Carlo code TRIPOLI4
("Improved PB modelling")



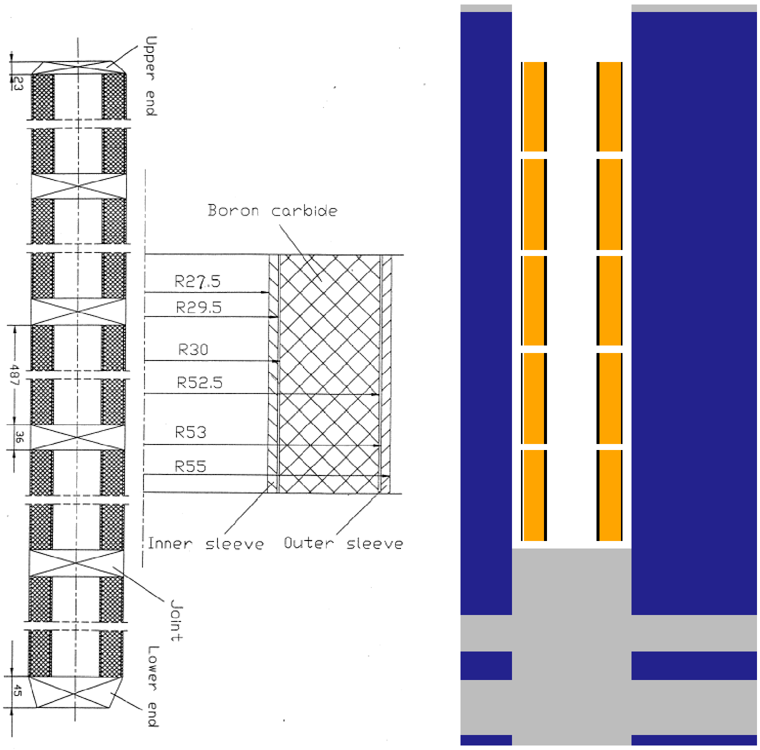
1.3.2 Void channels modelling

In the preliminary results given by CEA, all the calculations were performed in TRIPOLI4 without modelling the void channels (control rods and coolant channels). The consequence was an over-estimation of the core reactivity during the criticality approach. For all the calculations presented in this paper, the void channels have been described exactly in the Monte-Carlo code TRIPOLI4. The cavities modelling impact on reactivity (streaming effect) has also been evaluated for an intermediate core configuration close to the critical core configuration.

1.3.3 Control rods modelling

Ten control rods are designed in the side reflector of HTR-10. Each control rod contains five B4C ring segments, which are housed in the place between an inner and outer sleeve of stainless steel. In TRIPOLI4, the control rods have been modelled explicitly (Figure 6). It means that the annular geometry of the control rod has been modelled as well as the joints between the segments (3,6 cm height).

FIG. 6 Control Rods modelling in Monte-Carlo code TRIPOLI4



Control rod design **Control rod modelling in TRIPOLI4**

2. BENCHMARK DATA AND VOID CHANNELS MODELLING IMPACT

2.1. VOID CHANNELS MODELLING IMPACT (STREAMING EFFECT)

Some calculations have been performed with the Monte-Carlo code TRIPOLI4 in order to evaluate the impact of the void cavity modelling on the core neutron leakage. The results are presented in Table 2. In the first calculation (case a), the void channels (coolant and control rods channels) are homogenised with the surrounding graphite. In the second calculation, all the cavities have been described exactly in TRIPOLI4 (case b). In the selected configuration (the height of the pebble bed is approximatively 123.0 cm), the streaming effect has been evaluated to **1.48%Δk/k**.

TABLE. 2 Evaluation of the streaming effect in HTR-10

	TRIPOLI4 Case (a) Homogenised cavity	**TRIPOLI4** Case (b) Exact modelling	**Δk [%Δk/k]**
Core $k_{eff} \pm \sigma$ Pebble bed height = 123.06 cm	1.03586 ± 0.00034	1.01960 ± 0.00043	1.48

2.2. ANALYSIS OF THE BENCHMARK DATA IMPACT

After the HTR-10 core physics benchmark problems were defined, two conditions changed and concerned the dummy balls loaded into the core and the core atmosphere at initial criticality. The following list summarizes the deviations [4]:

- Density of dummy balls: from **1.73** to **1.84 g/cm^3**
- Boron equivalent of impurities in dummy ball: from **1.3** to **0.125 ppm**
- Core atmosphere at initial criticality: from **Helium** to **Air**

Considering the new benchmark data, some calculations have been performed with TRIPOLI4 in order to evaluate the impact on the core k_{eff}. The results that are presented in Table 3 are related to a core loading height of 123.06 cm. The decrease of the boron equivalent impurities in the dummy balls induces an increase of the core reactivity higher than the capture increase of air atmosphere. The impact on core reactivity amounts to **0.70%.**

TABLE. 3 Benchmark data impact

	TRIPOLI4 Helium	**TRIPOLI4** Air + impurities + density	**Δk [%Δk/k]**
Core $k_{eff} \pm \sigma$ Pebble bed height = 123.06 cm	1.01960 ± 0.00043	1.02669 ± 0.00048	0.70

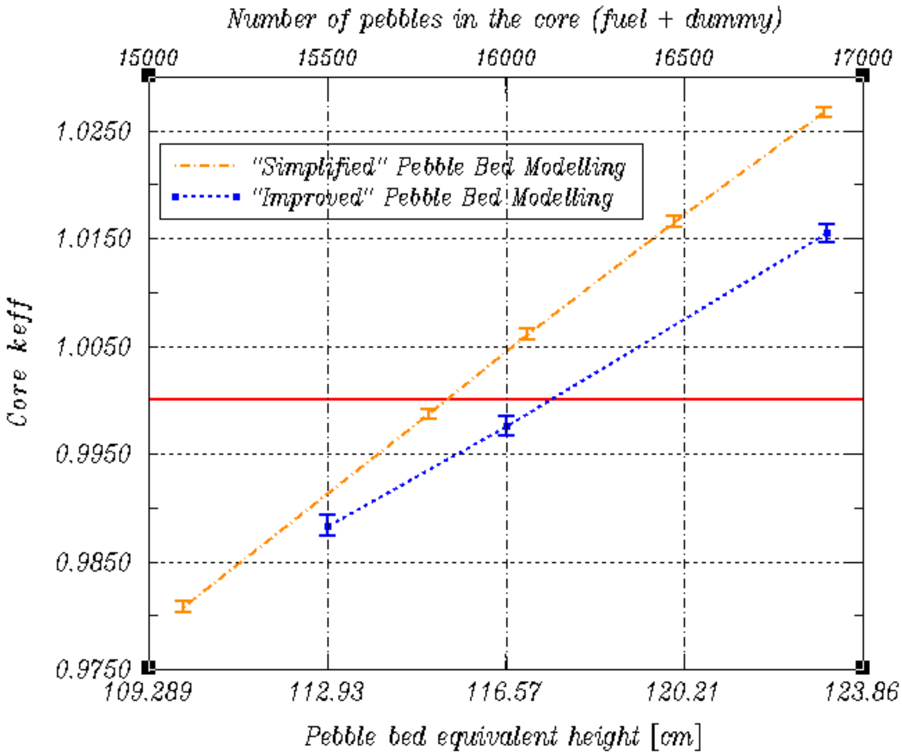
3. BENCHMARK RESULTS

3.1. INITIAL CRITICALITY (PROBLEM B1)

The aim of the first benchmark problem was to evaluate the amount of loading (given in loading height, starting from the upper surface of the conus region) for the first criticality, under air atmosphere and core temperature of 20 °C, without any control rods being inserted. The core multiplication factor has been calculated for different core loading heights with TRIPOLI4 by using the two types of modelling described below. The results are summarized in Figure 7.

On the one hand, it should be noticed that for the core configuration close to the criticality, the core effective multiplication coefficient increases linearly with the number of pebbles loaded. On the other hand, the pebble bed modelling has a strong impact on the core k_{eff}. For example, the discrepancy between the simplified and the improved pebble bed modelling reaches 0.9% Δk/k for a core loading height of 123.133 cm. This discrepancy is lower when the number of pebbles loaded into the core decreases but in all cases, the core k_{eff} obtained with the improved PB modelling is lower than the one obtained with the simplified PB modelling.

FIG. 7 Calculated k_{eff} vs loading height for HTR-10 initial criticality



In order to evaluate the impact of the pebble bed modelling on the results, calculations have been performed in a simplified configuration (infinite medium with white boundary condition). It allowed evaluating the impact of the pebble bed geometrical description without considering core physical effects such as streaming effect and spectrum transient at the interface between core and reflector. The results are gathered in Table 4. The $k_{infinity}$ calculated with both modelling (homogenised pebble bed or randomly distributed pebble bed) are very closed. It shows that the two types of pebble bed modelling are equivalent in infinite medium.

TABLE. 4 Pebble bed modelling impact in infinite medium

Pebble bed in infinite boundary conditions	**TRIPOLI4 Simplified PB** modelling	**TRIPOLI4 Improved PB** modelling	**Δk [%Δk/k]**
$k_{infinity} \pm \sigma$	1.76431 ± 0.00051	1.76155 ± 0.00125	0.15

After all, the discrepancies observed between the two modelling on the core geometry could be explained by:

- an underestimated streaming effect in the case of an homogenised pebble bed modelling,

- an overestimation of the fission rates in the region close to the reflector in the case of the *"Simplified BP Modelling"*. The pebble bed geometrical modelling seems to have a strong impact in the regions where the neutron spectrum transients are important (at the interface between active core and reflector). Besides, this phenomenon increases when the size of the core decreases (the radius of the active core is 90 cm).

As far as the benchmark problem is concerned, the critical heights calculated with the two models are presented in Table 5. With the **simplified PB modelling**, the criticality is achieved with a loading height of **115.36 cm**. This loading height is equivalent to **15833 pebbles** (fuel and moderator pebbles) loaded into the core. With the **improved PB modelling**, the criticality is achieved with a loading height of **117.37 cm** that corresponds to **16108 pebbles** loaded.

TABLE. 5 Critical height for the differentHTR-10 modelling

B1	TRIPOLI4 **Simplified PB** modelling	TRIPOLI4 **Improved PB** modelling
Critical height [cm]	**115.36**	**117.37**
Number of pebbles loaded		
Total	**15833**	**16108**
Fuel	~ 9025	~ 9182
Moderator	~ 6808	~ 6926

3.2. TEMPERATURE COEFFICIENT (PROBLEM B2)

Only the calculations at 20 °C with an equivalent core loading height of 180,12 cm (24721 pebbles in the core) have been performed. The results are gathered in Table 6. The core k_{eff} reaches **1.15679** with the simplified PB modelling and **1.14737** with the improved PB modelling. The discrepancy observed between the two modelling is about 0.9% for the full core configuration.

TABLE. 6 k_{eff} at full core

B21	TRIPOLI4 **Simplified PB** modelling	TRIPOLI4 **Improved PB** modelling
Core $k_{eff} \pm \sigma$ Pebble bed height = 180.12 cm (full core)	1.15679 ± 0.00040	1.14737 ± 0.00123

3.3. CONTROL ROD WORTH FOR THE FULL CORE (PROBLEM B3)

The reactivity worths of the ten fully inserted control rods (**B31**) and of one fully inserted control rod (**B32**, the other rods being withdrawn) have been calculated for the full core configuration. The results are presented in Table 7. The calculations have been performed with both pebble bed modelling and the reactivity worth is calculated by using the formulation:

$$\Delta\rho = \frac{k_{eff}(rods\ in) - k_{eff}(rods\ fully\ withdrawn)}{k_{eff}(rods\ fully\ withdrawn)} \qquad (1)$$

The reactivity worth of ten control rods has been evaluated to **13.06%** with the **simplified PB** modelling and **13.44%** with the **improved PB** modelling. In addition, the reactivity worth of one control rod has been evaluated to **1.35 / 1.31%.** If the core k_{eff} depends on the pebble bed modelling, on the opposite, the reactivity worth of the control rod(s) calculated in both cases are similar.

TABLE. 7 k_{eff} and reactivity worth of control rods for full core ***(core height = 180.12 cm)***

	TRIPOLI4 **Simplified PB** modelling		TRIPOLI4 **Improved PB** modelling	
Core $k_{eff} \pm \sigma$ (rods fully withdrawn)	1.15679 ± 0.00040		1.14737 ± 0.00123	
	B31 (Ten rods fully inserted, 27 °C)	**B32 (One rod fully inserted, 27 °C)**	**B31 (Ten rods fully inserted, 27 °C)**	**B32 (One rod fully inserted, 27 °C)**
Core $k_{eff} \pm \sigma$	1.00562 ± 0.00030	1.14120 ± 0.00041	0.99297 ± 0.00099	1.13225 ± 0.00110
Control rod(s) worth [%Δk/k]	13.06 ± 0.07	1.35 ± 0.08	13.44 ± 0.26	1.31 ± 0.29

3.4. CONTROL ROD WORTH FOR THE INITIAL CORE (PROBLEM B4)

As for the benchmark problem B31, the reactivity worth of the ten control rods has been calculated for an intermediate core loading height of 126 cm. All the results are gathered in Table 8. The reactivity worth of ten control rods has been evaluated to **13.66%** with the **simplified PB** modelling and **13.58%** with the **improved PB** modelling.

TABLE. 8 Reactivity worth of ten control rods for intermediate core ***(core height = 126.0 cm)***

	TRIPOLI4 **Simplified PB** modelling	TRIPOLI4 **Improved PB** modelling
Core $k_{eff} \pm \sigma$ (rods fully withdrawn)	1.03532 ± 0.00055	1.03211 ± 0.00085
	B41 (Ten rods fully inserted, 27 °C)	**B41 (One rod fully inserted, 27 °C)**
Core $k_{eff} \pm \sigma$	0.89390 ± 0.00038	0.88960 ± 0.00108
Control rods worth [%Δk/k]	13.66 ± 0.1	13.80 ± 0.20

In the second part of the benchmark problem B4, the differential reactivity worth of one control rod for the initial core (loading height of 126.0 cm) has been calculated with the simplified PB modelling. The results are reported in Table 9. The integral worth of one control rod was determined to be **1.52%.** Even if the experimental conditions were not the same as specified in the benchmark (the main differences were in the control rod elevation height and the amount of loading in the reactor core), the calculation result can be compared to the experimental value. Thus, the experimental integral worth of one control rod was determined to be **1.437%.** The calculated value agrees well with the experimental results.

TABLE. 9 Reactivity worth of one control rod for intermediate core ***(core height = 126.0 cm)***

	TRIPOLI4 - Simplified PB modelling **B42** (One rods, 27 °C)	
Axial position of the control rod [cm]	**Core $k_{eff} \pm \sigma$**	**Differential control rod worth [%Δk/k]**
Fully withdrawn	1.03532 ± 0.00055	*
230.318	1.03244 ± 0.00033	0.28 ± 0.10
279.018	1.02833 ± 0.00036	0.68 ± 0.10
282.618	1.02772 ± 0.00060	0.73 ± 0.12
331.318	1.02225 ± 0.00033	1.26 ± 0.10
334.918	1.02103 ± 0.00033	1.38 ± 0.10
383.618	1.01999 ± 0.00032	1.48 ± 0.10
394.200	1.01957 ± 0.00080	1.52 ± 0.13

CONCLUDING REMARKS

The HTR-10's core physics benchmarks have been treated with a Transport – Monte-Carlo calculation scheme (APOLLO2 – TRIPOLI4 calculations) and by considering two different modelling for the pebble bed geometrical description. In the "*Simplified PB Modelling*", the pebble bed has been represented by a homogeneous medium. In the "*Improved PB Modelling*", each pebble has been represented in the core (moderator and fuel pebbles). In both case, the double heterogeneity (fuel particles in a graphite matrix) and the self-shielding of the heavy nuclides have been treated by APOLLO2.

Due to the streaming effect and the small size of the core (90 cm in radius), the *"Simplified PB modelling"* always overestimates the core $k_{effective}$. As a consequence, the critical pebble bed height calculated with the *"Simplified PB Modelling"* **(115.36 cm – 15833 pebbles in the core)** is much more lower than the one calculated with the *"Improved PB Modelling"* **(117.37 cm – 16108 pebbles in the core)**. These discrepancies between both models are also observed for the fully loaded (problem B2) core and for the intermediate core configuration close to the criticality (pebble bed height of 126 cm). Finally, the control rods worth evaluated with both modelling are very closed from each other (problem B31 & B32).

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