HTR-N

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High-Temperature Reactor Physics and Fuel Cycle Studies
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HTR-N

Technical Summary Report of the WP1

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INTRODUCTION

HTR appears as a promising concept for the next generation of nuclear power reactor. In this context, the European scientific community must have operational tools to perform as well conceptual design studies, industrial calculations as best-estimate or reference calculations. This implies in a near future, besides Monte Carlo codes, to have methods based on multigroup diffusion and transport codes able to model the HTGR core with its inherent characteristics whatever the concept may be (pebble bed or block-type reactors).

Indeed, a survey on the inherent HTGR characteristics lets appear that they have a strong impact on the core modelling related issues. Several points can be identified:

- The use of helium gas as coolant in HTGR leads to an important void fraction in the core consequently to large **neutron streaming** effect.
- the use of graphite a large part of the neutron population is in the epithermal range of energy. Therefore, the classical **self-shielding treatment** of the resonances amplifies the existing imperfections of the models, which until now led to well-mastered uncertainties for the others reactors.
- Compare to a pin-fuel with a clad, the fuel dispersion in a form of micro-particles allows to envisage **very high burn-up**. The immediate consequence concerns the mastery of the uncertainties in fuel depletion calculations
- It is often mentioned that the HTGR is highly flexible and can fulfil a wide range of diverse fuel cycles by accommodating physical parameters such as the fuel loadings (particle volume fraction in the graphite), the type of fuel, the burnable poisons, fissile/fertile fuel particle fraction, etc... The resulting core **configurations** are often strongly **heterogeneous** with important space dependent variations of the neutron spectrum.
- Finally, the fuel in a form of dispersed particles on the one hand and, the treatment of the pebble bed core on the other, impose a **stochastic approach of the geometry** in the Monte Carlo calculations. This may question the principle of the unbreakable reference that constitutes the Monte Carlo methods

Therefore, in order to take into account, in the HTGR core physics studies, all the characteristics detailed above, some calculation schemes have been developed in the past and continue to be improved (Figure 1).

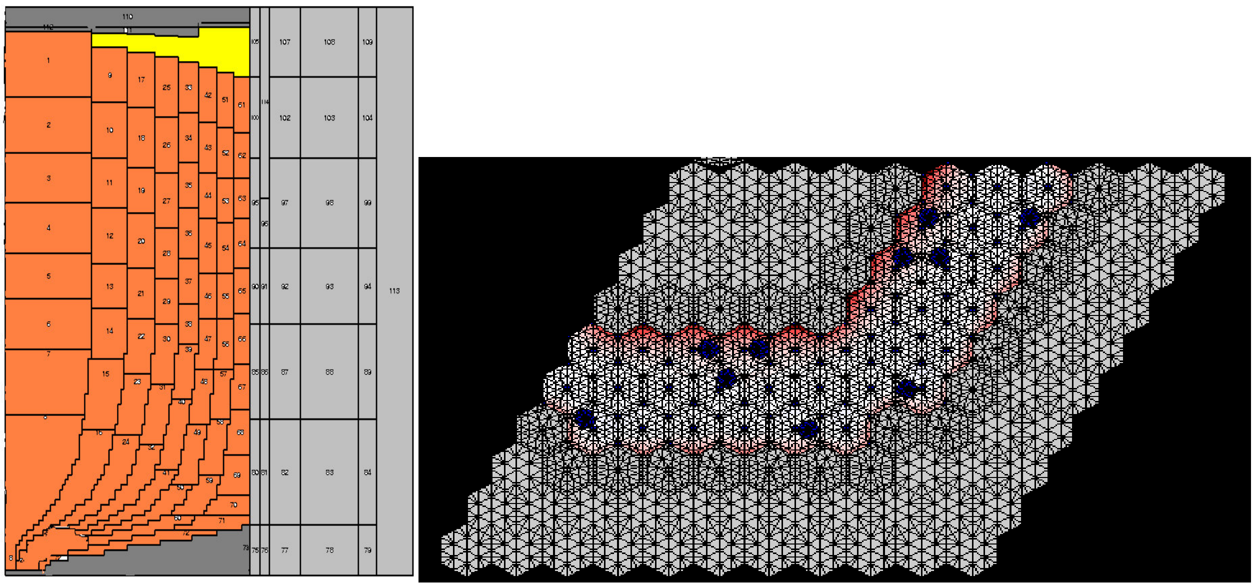


Figure 1: Example of Pebble bed and Prismatic core modeling: zone subdivision of HTR-MODUL-200 reactor in VSOP/CITATION and Finite Element diffusion calculation with CRONOS on the GT-MHR.

Core physics calculation tools are available today both for pebble bed and block-type core. However, these codes and methods are validated for the former HTGR concept conditions and for a limited set of fuel types, such as uranium or U/thorium. Additional requirements appear today, on one hand the codes and their associated methods may have progressed and on the other hand, the **HTGR design evolutions** and changes lead today to some **new core configurations** for which references do not exist:

- Annular core geometry
- Type of Fuel (plutonium & minor actinides burning, waste minimisation strategy)
- Ultra high-burn-up …

In order to be able to take into account these additional requirements, validation and qualification steps are always needed. For all these reasons described above, the main objectives of the Work Package 1 (WP1) was:

- to contribute to the code validation
- to qualify and improve the methods for modeling the HTGR

The present report provides only an overview of the work that has been done through the WP1 of HTR-N. The complete analysis of the results is however available on each Task Report of the WP1.

1. DESCRIPTION OF THE TASKS IN THE WP1

HTTR and HTR-10 are two reactors recently started-up respectively in Japan (1998) and in China (2000). Both reactors are representative of both HTGR concepts that are envisaged today: block-type and pebble bed reactors. Therefore, it was decided that all the works that might be done in the WP1 would be based on the analysis of these two reactors. This work package would then allow demonstrating the capabilities of the European code systems as well as identifying the calculation method deficiencies or the lack of theoretical model, which could exist in these tools.

It is noteworthy that all the calculations performed through this work package only concerned reactor cores at *cold zero power*. This means that the analysed critical states of each reactor correspond to such a low neutron flux that no power is generated in the fuel elements. This avoids taking into account the temperature feedback on the neutronic calculations with the associated hypotheses on the thermal-hydraulics modelling. However, the power configurations of the HTTR and HTR-10 will allow validating such a coupling calculations and should be addressed in a near future.

Moreover, for both reactors the fuel can be considered as fresh fuel. In these conditions, uncertainties related to fuel depletion calculations do not occur.

Finally, one should note that these two reactors use low enriched uranium (less than 20 %). Even though that completes the qualification steps that have existed in the past on uranium fuels, the present WP1 studies cannot serve to quantify the uncertainties that could exist with the plutonium cycle studies performed on the WP3. Indeed, to study plutonium fuel cycles in HTGR imply fuel depletion calculations at very high burnup for which calculation discrepancies are already observed for standard PWR's burnup (differences in nuclear data but also in the treatment of the resonances of the higher plutonium isotopes). Nothing is available today for qualifying the codes on plutonium or minor actinides fuels in an HTGR.

The following repartition was adopted in the **WP1**:

- The task 1 had to focus on the HTTR first criticality stage. This stage represented the first opportunity in reactor physics to model and benchmark the codes and methods in thin annular core geometry.
- The task 2 had to tackle all the others configurations of the HTTR, between the first criticality and the fully loaded core configuration, that have been achieved and for which experimental measurements was available.
- The last task 3 was similar to the first one and was devoted to the estimation of the amount of fuel pebbles needed to get critical the HTR-10 reactor.

One should note that all the works that had been scheduled for the WP1 of the HTR-N contract has been carried out. However, a non-negligible part of the works has been done through the Coordinated Research Project-5 of the IAEA [1]. But, it should be pointed out that the HTR-N contract was a good opportunity to analyse the first results and to perform additional calculations for explaining the observed discrepancies.

2. TASK 1: HTTR's FIRST CRITICALITY CONFIGURATION

As far as the HTTR is concerned, this action has been launched following the great discrepancies observed on the international results of the HTTR-FC benchmark in which the number of fuel columns to achieve criticality had to be predicted (**WP1's Task 1**). The fuel columns were gradually loaded one after another from the outer region of the core (see Figure 2). In these conditions, a thin annular core configuration was obtained in course of loading (18 columns, left part of the figure 2), the rest of the core being loaded with some dummy fuel blocks. It turns out that the first criticality has been achieved with 19 columns the core being almost critical in its annular configuration.

This specific geometry is very close to the one that can be encountered in current HTGR designs proposed today, i.e. GT-MHR and PBMR-SA [2]. It represents one of the first opportunities to model such core geometry and to be able to compare with the experiment. Finally, the excess reactivity for 18, 24, and 30 fuel columns in the core had to be evaluated and form also the subject of the benchmark HTTR-EX and of the present WP1's Task 2.

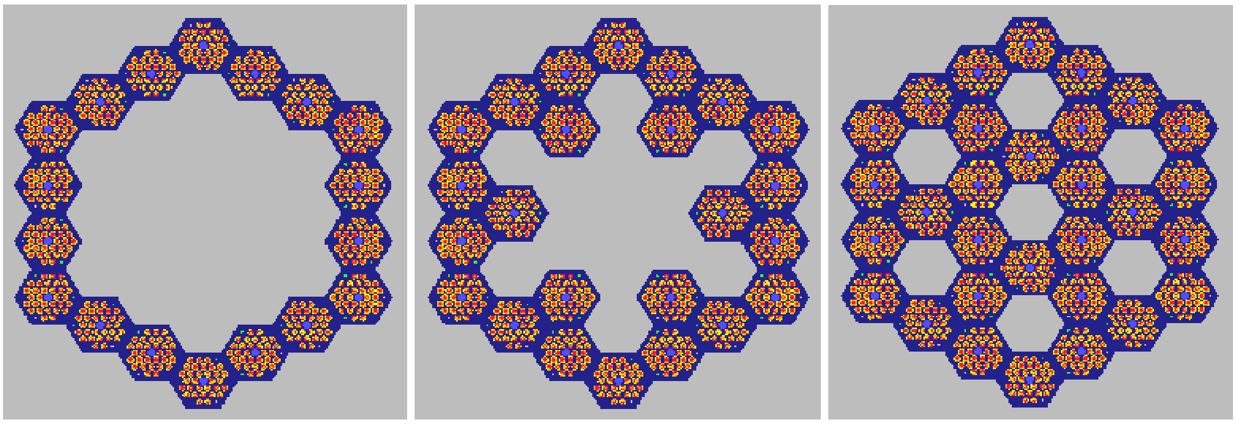


Figure 2: HTTR core configurations analysed during the WP1 studies.

As far as the Task 1 related technical results are concerned, it should be pointed out that first an important analysis and interpretation of the former HTTR-FC benchmark results have been done in order to tentatively explain the discrepancies with the experiment. Then, different strong assumptions or physical hypothesis in the HTTR modeling have been identified and their effects quantified by the partners. A very good coherence between the code systems for quantifying the impact of three common physical effects has been observed (Figure 4).

The discrepancy between the former calculational results and the experiment ranges from $\Delta k = 0.017$ to 0.058 at 18 fuel columns loading (near the first criticality), and from $\Delta k = 0.01$ to 0.052 at full core. Thus, related work in HTR-N had to focus on the reasons for these deviations and to provide an improved modelling of the thin annular core geometry. It is important to take accurately the complex fuel element structure (Figure 3), the core/reflector interfaces associated to important axial and radial heterogeneities in the core (burnable poison, many different enrichments) and the presence of a large number of uncommon large channels offering the possibility for the neutrons to leak from the active zone (streaming effect) into account.

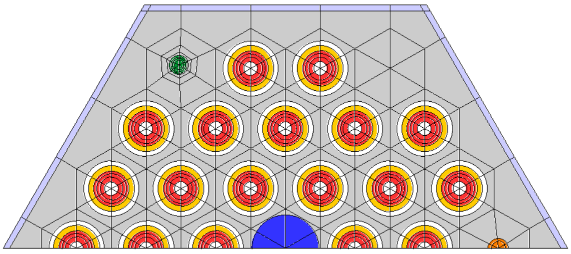


Figure 3: 2D fuel element description in APOLLO2 transport calculations

The nuclear data libraries used by HTR-N partners are based on the JEF2.2 evaluation. Two Monte Carlo codes are used to model the HTTR: the KENO code at IRI, associated with a multi-group approximation (172 groups), provided by the SCALE4 code system, and the TRIPOLI4 code at CEA using point-wise cross sections everywhere in the core except in the fuel rod region where multi-group cross sections (172 groups) are generated by the transport code APOLLO2 in order to treat the double heterogeneity of the coated fuel particles (CFP). The 1d or 2d transport / 3d diffusion code systems: WIMS/PANTHER, SCALE4/BOLD VENTURE, APOLLO/CRONOS, and TOTMOS-DORT / CITATION are used at NRG, IRI, CEA, and FZJ, respectively. The double heterogeneity of the CFPs and the self-shielding in the resonance region are taken into account in all cell calculations.

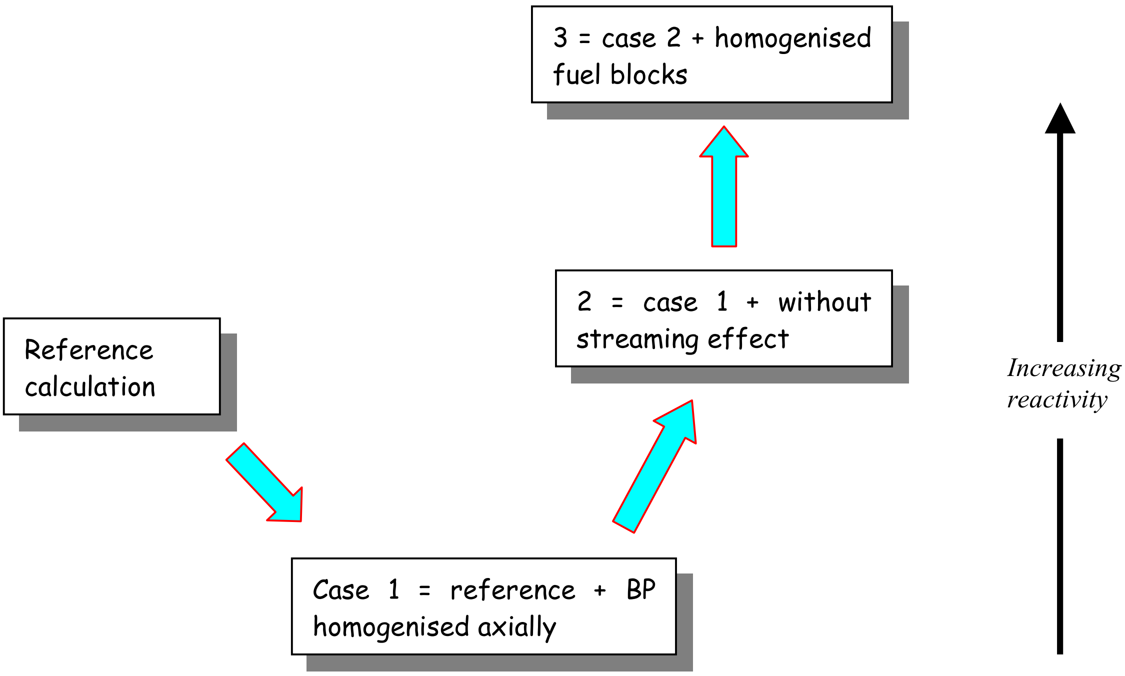


Figure 4: Modelling hypotheses: effect on the reactivity

In the course of the **HTR-N studies**, the following reasons for the discrepancies have been identified and quantified by the different code systems.

- neglect of the detailed structure of the HTTR fuel block together with a non-adequate modelling of the fuel and burnable poison (BP) unit cells, (case 3)
- inadequate treatment of the axial self-shielding in the BP rods (case 1)
- underestimation of the neutron streaming (case 2)

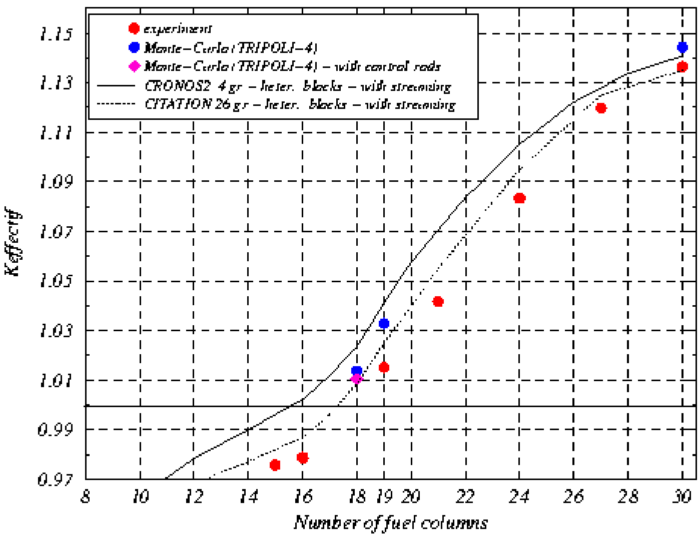
They are depicted on Figure 4 as a function of the reactivity.

Finally, revisited data of the HTTR-FC benchmark have been proposed by the Japanese and have been a good opportunity to recalculate the reactor taking into account the method improvements coming from the previous analysis. A great progress in predicting the first criticality of the HTTR (thin core configuration – 18 columns) is obtained. For example, the number of fuel columns needed to achieve criticality increases by about 7 (CEA) and 2 (FZJ) in comparison with the former results. The possible reasons related analysis to explain the remaining small differences between diffusion and Monte Carlo code is almost completed.

A complete description of the codes, methods and modelling hypotheses as well as the detailed analyses and interpretations of the obtained results are available in the Task Report HTR-N-02/05-D-1.1.1.

3. TASK 2: OTHERS CORE CONFIGURATION OF THE HTTR

As far as the **WP1's Task 2** is concerned, it was dedicated to the analysis of the other HTTR core configurations. Indeed, others core geometries than the thin core first criticality configuration, have also largely been tackled. This study took part of the analysis described above and carried out in the Task 1. It should be stressed that, quite acceptable discrepancies have finally been obtained on the **fully loaded core configuration** between the experiment and both probabilistic and deterministic calculation methods. However, it must be pointed out that the discrepancies initially observed for the thin core, decrease with increasing number of fuel columns in the core. Due to the large experimental error at 30 fuel columns loading (full core), the differences between the calculations and the experiment are within the error interval, whereas at the thin annular core assembly the discrepancies remain non-negligible.



As a concluding remarks, one could say that, based on the revised data of the HTTR benchmark, the recalculation of the first criticality with the TRIPOLI-4 **Monte Carlo** code allowed to reduce the discrepancy by about a factor two (from ~ 2 % to 1 % Δk/k). On the other hand, the result obtained for the fully loaded core configuration is quite acceptable taking into account the uncertainties associated with the experimental values. The remaining deviation for the thin annular core (first criticality) might be explained by the uncertainties of the graphite impurities for which the impact is very important in this core configuration (dummy fuel blocks in pure graphite in the central part of the core).

From these considerations, the Monte Carlo results should be used to compare and to qualify the methods employed in the **diffusion calculation.** New implemented methods coupled with new benchmark data allowed obtaining good enough results for all the 3D diffusion calculations in the full core configuration. Near the first criticality, the number of fuel columns needed to achieve criticality increases by about 7 (CRONOS-2) and 2 (CITATION) in comparison with the former results. All final results are given in Table 1. In the case of the Monte Carlo code TRIPOLI, the discrepancy between measurement and calculation at the first criticality is reduced to Δk/k ~ 0.85 %, when considering the revised data of the HTTR benchmark. As to the diffusion codes, this discrepancy is now reduced to Δk/k ~ 0.8 %(CITATION) and ~ 2.75 % or 1.78 % (as a function of the energy groups in CRONOS-2), when taking account the improved treatments and the revised data.

Table 1: The new core calculations together with the experimental results

	CITATION	TRIPOLI	CRONOS	EXPERIMENT
	Diffusion 26 groups	M. Carlo 172 gr. & pointwise	Diffusion 8 groups - 4 groups	
	3D triangular	3D	3D hexagonal	
	3 reg./block		3 reg/block	
	finite difference		finite element	
	24 meshes/block		24 meshes/block	
30 col.	**1.1336**[1)]	**1.13833**[2)] **± *0.00090***	**1.1451**[2)] **- 1.1362**[2)]	**1.1363 ± (> *3.6 %*)**
24 col.	**1.0944**[1)]	**-**	**1.1096**[2)] **- 1.1000**[2)]	**1.0834 ± (> *2 %*)**
19 col.	**1.0263**[1)]	**1.02692**[2)] **± *0.00043***	**1.0432**[2)] **- 1.0351**[2)]	**1.0152 ± ?**
18 col.	**1.0080**[1)]	**1.00855**[2)] **± *0.00090***	**1.0275**[2)] **- 1.0178**[2)]	**subcritical**

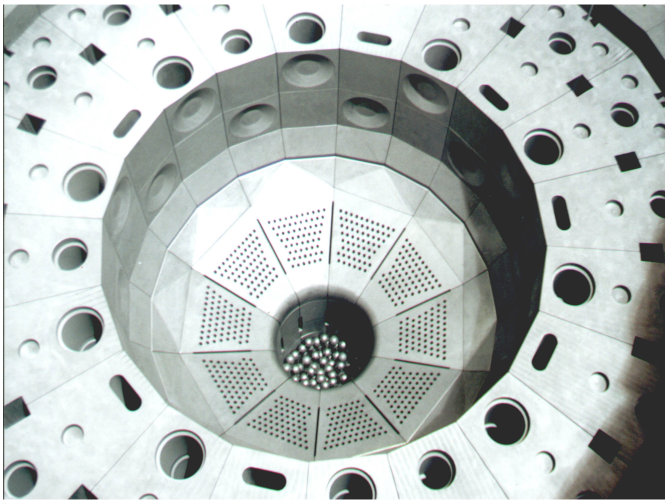
[1)] *CR inserted considered Δk = 0.004 and detector impact included Δk = 0.002*
[2)] *detector impact included Δk = 0.002*

Finally, it turns out that the following procedures seem to be necessary for a better approach to the experimental results:

- detailed heterogeneity of the burnable poisons- and fuel-region in the whole core calculation,
- use of fine group constants in the whole core (FZJ) diffusion calculation or the consideration of the actual environment of the fuel blocks in the (as it has been done by NRG) transport cell calculations in order to describe the core/reflector coupling accurately
- consideration of the axially heterogeneous distribution of the burnable poisons by 2D cell calculations (FZJ) or by 3D diffusion calculations (CEA and NRG)
- treatment of the enhanced neutron streaming whether by an adaptation of the diffusion constants to Monte Carlo calculations (FZJ) or by a leakage model combined with an analytical model (CEA).

4. TASK 3: HTR-10 FIRST CRITICALITY ANALYSIS

Another benchmark available is the Chinese 10 MW test reactor HTR-10 at the INET in Beijing, which reached first criticality End of 2000. It has a 17% enriched LEU pebble bed core. Absorber rods in the reflector exclusively control reactivity. Despite the small power size of HTR-10, it is a nearly 1:1 scale test for a modular HTR because the radial dimensions of the reflector blocks are identical to the commercial size. Therefore, HTR-10 can be seen as a representative test for the passive decay heat removal and for verification of codes especially with regard to the effectiveness of the shut-down systems.



To achieve first criticality, the fuel discharge tube and the cone of the core bottom has been filled with graphite pebbles only. Thus, the active core has de facto a cylindrical shape when adding fuel and graphite pebbles from the top except a conical heap-up on the surface of the pebble bed core. **The reactor finally got critical with 16890 pebbles. Assuming a filling fraction of 0.61 of the pebbles in the core cavity, an effective core height of 123,1 cm is needed to get critical the reactor.**

Then the **WP1's Task 3** had to tackle the HTR10-FC benchmark, where the objective was to evaluate the amount of pebble-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 HTR-10's core physics benchmarks have been treated:
- with two Transport-Diffusion calculation schemes WIMS/PANTHER and VSOP(CITATION)
- with a Transport-Monte-Carlo calculation scheme (APOLLO2 – TRIPOLI4).

After the blind calculation (*defined benchmark* - before the actual first core criticality), the data of the benchmark was corrected in order to be closer to the experimental configuration (*revised benchmark*). This allow taking into account air in the core instead helium, a new level of impurity in the graphite, … The calculational results of the original and the deviated benchmark problems are summarised in the following Table.

Critical level in cm	Defined bench.	Revised bench.
Diffusion with VSOP(2D)	124.2 cm	121.0cm
Diffusion with VSOP(3D)	126.8 cm	123.3 cm
Diffusion with PANTHER	125.3cm	122.1 cm
Monte Carlo with TRIPOLI		117.4 cm

Table 2: HTR-10 benchmark results. Critical core level.

It can be noticed that there is a discrepancy of about 1% between the 2-d VSOP and the 3-d VSOP calculations considering the neutron streaming in the channels of the control rods and small absorber balls explicitly. However, it has to be pointed out that **diffusion calculations agree well** with each other and with the experiment.

As far as the Monte Carlo calculations are concerned, two different modelling for the pebble bed geometrical description have been considered. In the "*Simplified PB Modelling*", the pebble bed has been represented by a homogeneous medium. In the "*Improved PB Modelling*" (result in Table 2), 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"* is much more lower than the one calculated with the *"Improved PB Modelling"* (given in Table 2).

Therefore, one can note that this **preliminary approach for modelling the stochastic geometry** of the HTR-10 in the **Monte Carlo** calculations leads to an **overestimation of the core reactivity**. The pebbles have been initially arranged according to a *Face Centred Cubic* lattice with a packing fraction of 74 %. Then, some pebbles have been removed, respecting the fuel/moderator ratio, in order to reach the actual filling fraction of 61 %. This arrangement lets appear some cavity in the pebbles bed and an inhomogeneous pebble distribution that might have a strong influence on the reactivity.

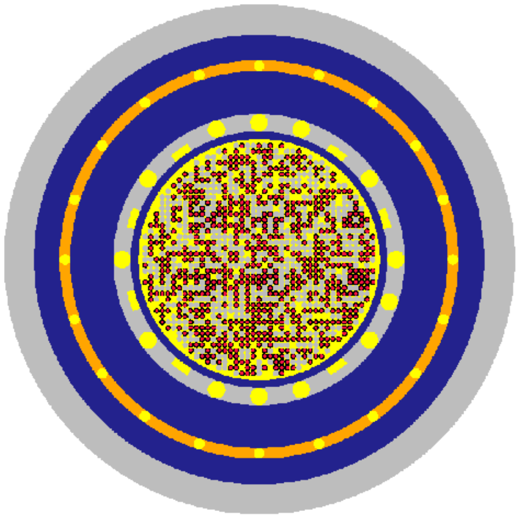


Figure 4: Monte Carlo geometry of the HTR-10 (TRIPOLI4)

The reason for such a difference in the results remains nevertheless to be investigated furthermore, but recent publications underscored that significant impact could be related to, on one hand the geometric description of the pebble bed in the core cavity and, on the other hand the geometric description of the particles insides the pebbles. This formed the subject of a following study in the **WP1 (Task3) of the HTR-N1 contract**.

A complete description of the codes, methods and modelling hypotheses as well as the detailed analyses and interpretations of the obtained results are available in the Task Report HTR-N-03/06-D-1.3.1.

5. DELIVERABLES AND SUPPORT DOCUMENTS

All the documents available on the Web SINTER site and related to the works that have been performed in this WP1 are listed below:

- HTR-N-02/05-D-1.1.1 - *Task Report*
  - HTR-N-00/12-D-1.1.2
  - HTR-N-01/06-S-1.1.3

- HTR-N-02/05-D-1.2.1 - *Task Report*
  - HTR-N-02/05-D-1.2.2
  - HTR-N-03/08-D-1.2.3

- HTR-N-03/06-D-1.3.1 - *Task Report*
  - HTR-N-02/09-D-1.3.2
  - HTR-N-02/09-D-1.3.3
  - HTR-N-03/06-S-1.3.4

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