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Technical Summary Report of the WP1 of HTR-N1

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INTRODUCTION

Contrary to the past, where R&D activities were based on and often supported by large experimental programs, less effort will be devoted to experiments in the next conceptual design activities performed in a near future. Indeed, because of the cost of the experiments and the low available means today to set up nuclear experiments, future design and conceptual studies will use intensively predictive calculations.

This implies to have high-performance computational tools and calculation processes, which will give credible results, associated to a high level of confidence. R&D European institutions have at the present day their own operational codes systems which should serve to define the next generation of nuclear power reactor like the HTR. Nevertheless, they are more or less validated and qualified and are often dedicated to specific concept. Particularly for the HTR, future computational tools should be reliable and able to perform all sort of multi-level calculations (design study, industrial calculation and reference or best estimate calculations) whatever will be the concept (type of fuel, pebble bed or bloc type core) to predict core depletion, reactivity margin (also taking into account thermal feedback), etc…

In order to be able to take into account these additional requirements, validation and qualification steps are always needed. 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 HTR-N&N1 would be based on the analysis of these two reactors. For all these reasons described above, the main objectives of the Work Package 1 (WP1) through the **HTR-N** contract was:

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

The present WP1 of the **HTR-N1** had to continue with this objective by focusing on the HTTR reactor, the prolongation action on HTR-10 being done in the WP2 of HTR-N1 contract. The following three tasks had then been adopted:

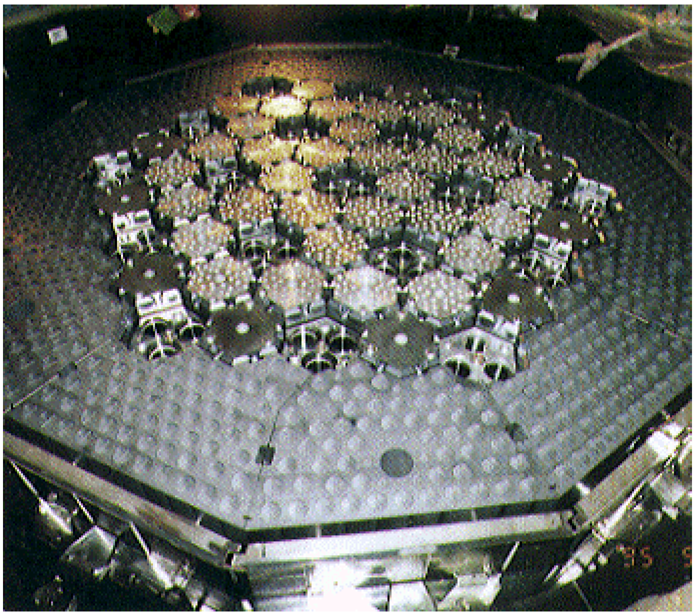
- In the task 1, it was scheduled to estimate the isothermal temperature coefficients of the HTTR core between the room temperature and about 200°C. The calculational results had to be compared to the experimental ones obtained by heating homogeneously the core.
- The task 2 foresaw an analysis of the reactivity worth of different configurations of the control rods inserted in the HTTR core.
- Finally, the last task 3 had to be initially dedicated to the analysis of the first criticality steps in power. Owing to the non-available experimental data of these power configurations, this small last task has been a good opportunity to come back to the previous unexplained discrepancies obtained with the HTR-10 problem: stochastic geometry modelling with Monte Carlo method.

One should note that whether almost all of the works that had been scheduled initially for the WP1 of the HTR-N1 contract has been carried out, a non-negligible part of the work has been done through the Coordinated Research Project-5 of the IAEA [1]. However, the HTR-N&N1 contracts were a good opportunity to analyse the former results and to perform additional calculations for explaining the observed discrepancies.

The present report provides only an overview of the work that has been done through the WP1 of HTR-N1. The complete analysis of the results is however available on each Task Report and support documents of the WP1.

1. TASK 1: HTTR's TEMPERATURE COEFFICIENTS

Until now, HTTR and HTR-10 calculations done in the **HTR-N's WP1**, have been performed at room temperature. It was planned, that additional calculations on the HTTR carried out in the **HTR-N1's WP1** had to take into account temperature feedback effects. Indeed, HTTR core configurations obtained during homogenous raised temperature might be available in a near future. They represent a succession of critical state during which feedback effects have to take place with more and more importance.



Before modeling these HTTR core configurations at different reactor power levels taking into account these temperature feedback effects, firstly, control rod modeling related problems must be solved and then, a good accordance has to be achieved between the partners on the evaluation of the obtained reactivity worth for an homogeneous temperature variation in the reactor at a hot zero power (isothermal temperature coefficient). The latter constituted the basis of the present **Task 1**: estimation of the isothermal temperature coefficients on the fully loaded core configuration at hot zero power and with fixed control rod position (HTTR-TC benchmark).

The computed results obtained for this benchmark are summarised in the following Tables. Indeed, the temperature coefficients have actually been calculated with the help of several codes for 6 temperatures varying from 280 K to 480 K. The temperature coefficients have then been evaluated from the following expression:

$$\rho_{12} = \frac{k_{T_1} - k_{T_2}}{k_{T_1} \times k_{T_2}} \cdot \frac{1}{(T_1 - T_2)}$$

They have been estimated from k_{eff} of 3D core transport and diffusion calculations performed at different temperatures. The Table 1 and 2 below give an example of the k_{eff} and deduced temperature coefficients obtained with CRONOS.

Table 1: k_{eff} as function of the temperature

Temperature [K]	APOLLO2 – CRONOS2
300	1,00395
340	0,99724
380	0,99088
420	0,98455
460	0,97823
480	0,97525

Table 2: Isothermal temperature coefficients

Temperature coefficients [pcm/°K]	APOLLO2 – CRONOS2
ρ_{320}	– 16,75
ρ_{360}	– 16,09
ρ_{400}	– 16,22
ρ_{440}	– 16,40
ρ_{470}	– 15,62

It should be noticed that according to the results gathered here, the temperature coefficients range from - 15 to - 16 pcm/°K between 300 K and 480 K respectively. In order to have a comparison between the different code systems, the evaluation of the temperature coefficient at 400 K is given below (Table 3).

It is noteworthy that the results are in relatively good accordance with the experiment where the values are comprised between - 13 and - 14 pcm/K at the same temperatures. One can conclude that compare to the experimental measurement the calculated temperature coefficients are overestimated by about 10 % in average by the different codes.

Table 3: Isothermal temperature coefficients for the HTTR[#]

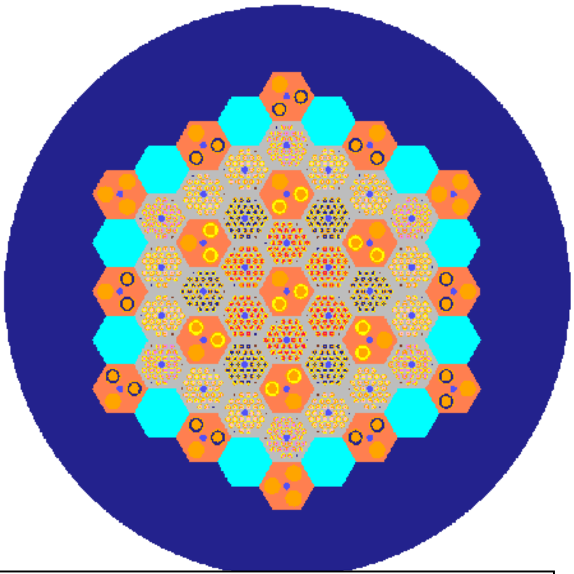
	KENO (IRI)	PANTHER (NRG)	CRONOS (CEA)	CITATION (UNIPI)
Core at 400 K	**- 14.7 pcm/K**	**- 15.2 pcm/K**	**- 16.2 pcm/K**	**- 17.2 pcm/K**

[#] CR group C, R1 and R2 inserted (178.9 cm)

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-N1-04/07-D-1.1.0-1_1.

2. TASK 2: CONTROL ROD WORTH IN THE HTTR

The objective of the **Task 2** was the evaluation of the control rod worth for different core configurations at hot zero power condition. Many configurations were available: scram reactivity of all the control rods, and scram reactivity of the reflector control rods only. Therefore, there was a continuation with the work performed in the previous contract (HTR-N) where control rod modeling is tackled on one or several core configurations. The expected results were an improvement of the control rod modeling in the core calculations.



Control Rod location : blue in the reflector zone and yelow in the core (TRIPOLI4 calculations)

The same codes have been used by UNIPI, CEA and NRG/IRI to estimate the control rod worth in the HTTR. The results given in the following Table correspond to the scram reactivity of the reflector control rods on the one hand, and on the other hand to the scram reactivity of all the control rods. This is done for the fully loaded core configuration (32 fuel columns in the core). The control rod positions of the experiment for obtaining criticality with all the inserted CR are: **178.9 cm**.

The results using 3D **PANTHER** calculations lead to the following:
k_{eff} = 1.0088 at critical position and k_{eff} = 0.7317 after scram of all control rods. That means a worth of 37.5% which appears very low compare to the other results but can be explained by neutron streaming in the control rod holes and is to be recalculated by means of anisotropic cross sections.

The others results are gathered in the Table 4. The reflector control rod worths are in well agreement with the values given by the other international participants of the IAEA benchmark, nevertheless an underestimation of the control rod worth could be underscored compare to the experiment in case a scram of reflector CRs.

Control position	**KENO**	**TRIPOLI4**	**CITATION**	**CRONOS2**	**Exp.**
178,9 cm	**1.0093 ± 0.0006**	**1.00117 ± 0.00024**	**1.0031**	**1.00020**	**Crit.**
177,6 cm		*0.99972 ± 0,00038*		*0.99840*	*
Scram of refl. CRs □	**0.9178 ± 0.0005** *9.88 %*	**0.92215 ± 0.0004** *8.56 %*	**0.86535** *15.87 %*	**0.90245** *10.83 %*	*12 % (± 1.2)*
Scram of all CRs □	**0.6809± 0.0005** *47.78 %*	**0.68396 ± 0.0003** *46.32 %*	**0.67937** *47.50 %*	**0.63982** *56.31 %*	*46 % (± 4.6)*

Table 4: Control Rod Worth in the HTTR: k_{eff} (initial state and scram) and $\Delta k/k$ in %

Likewise, these results underscore the fact that the CR worth is globally overestimated with the diffusion method compare to the Monte Carlo calculations, especially in this case where no equivalence factors have been used in order to respect either the flux or the absorption rates between the multi-group transport calculations and the broad group diffusion core calculations. Consequently, it is obvious that further investigations must be carried out in a near future in order to improve the CR modeling related problem especially for rods inserted in the reflector of a HTR. This problem is also addressed for the HTR-10 (HTR-N1's WP2).

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-N1-04/07-D-1.2.0-1_1.

3. TASK 3: HTR-10 FIRST CRITICALITY: ADDITIONAL ANALYSIS

The HTR-10's core physics benchmarks have been treated in the HTR-N's WP1:

- 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

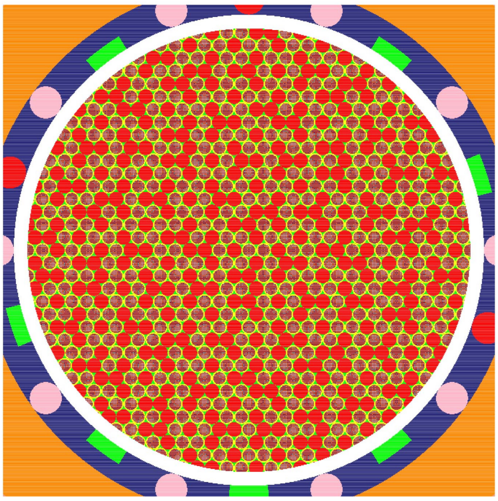
Table 5: HTR-10 benchmark results. Critical core level.

It can be noticed the biggest discrepancy comes from the Monte Carlo calculation. The 117.4 cm corresponds to an overestimation of the core reactivity of about 1.5 %. Therefore, it was suspected that a 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. **The present Task 3 was a good opportunity to explore the impact of the stochastic geometry modelling of a PBR with the Monte Carlo method.**

Pebbles in the core cavity

First of all, the way used **previously** for modeling the core cavity with TRIPOLI4 must be recalled. 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** including at the core/reflector interface that might have a strong influence on the reactivity.

Another approach was used during the works done in this Task. A column hexagonal point on point (CHPOP) arrangement of the pebble bed has been chosen to describe the core cavity. Indeed, the theoretical filling factor of 0.6046 is very close to the one observed experimentally (~ 0.61). This arrangement of balls in the discharge tube, in the bottom conus region and in the cylindrical part of the reactor core, corresponds to a hexagonal prism lattice in x- y plane and is top to top in z – direction. As shown in figure beside, in this ***exact core modeling***, the fuel-to-moderator pebble ratio of the initial HTR-10 core loading was taken into account. To do that, a specific treatment of a basic regular lattice was done in order to get as well the good filling factor as the good proportion and distribution of the fuel and dummy pebbles. The percentages of fuel balls and dummy balls obtained in the TRIPOLI4 calculations are 56.76% and 43.24% respectively. The filling factor is 60.46%.



Moreover, it is worth to mention that each layer is radialy shifted one by one of a half pebble along the axial direction. By using this shifted arrangement, the "artificial streaming" induced by the cavity between pebbles in the CHPOP model is avoided.

Fuel particle in the Pebbles

The stochastic geometries calculations (coated fuel particles -CFP- randomly distributed in the inner zone of the fuel pebble) are not directly possible in TRIPOLI4. Assumptions to model the fuel pebbles have been made. Three different models were adopted to describe the fuel zone of the fuel pebbles: a homogeneous model and two heterogeneous one. However, all the models were based on precise descriptions of the particles with their coatings. The coated fuel particles were uniformly placed according two regular lattices: the first one is a cubic lattice with edge and height of 0.199 cm, the other one is a simple hexagonal column lattice with edge of 0.241 cm and height of 0.209 cm. The last homogeneous description corresponds to some multi-group (172 gr) cross sections provided by APOLLO2 just for the internal fuel zone of the pebbles.

Results

Table 6 gathers the results obtained for those two different core models calculated with the same JEF2.2 library. It turns out that the obtained results with the ***exact core model*** are quite good compared to the experiment. By comparing with the previous calculations performed with TRIPOLI4 on that HTR-10 reactor [1] based on a different approach of the treatment of the core cavity, it underscores and confirms that the adopted manner to describe the **pebbles arrangement in a PBR is of importance with the Monte Carlo method**.

Table 6: HTR-10 benchmark results. Critical core level.

Core configuration in TRIPOLI4	k_{eff}	First Criticality (exp. 123.06 cm and 16890 pebb.)
Particles: 172 Multigr. Cross section in the fuel zone (APOLLO2) *Pebbles*: Cubic lattice + random removing		***117.4 cm*** *(16890 pebbles)*
Particles : Cubic lattice *Pebbles* : Hexagonal lattice(each layer shifted axially)	**0.99194 (70) – 120 cm** **1.01040 (70) – 126 cm**	**122.62 cm** *(16681 pebbles)*
Particles : Hexagonal lattice *Pebbles*: Hexagonal lattice (each layer shifted axially)	**0.99318 (60) – 120 cm** **1.01114 (61) – 126 cm**	**122.30 cm** *(16637 pebbles)*
Particles : 172 Multigr. Cross section in the fuel zone (APOLLO2)*Pebbles*: Hexagonal lattice (each layer shifted axially)	**0.99050 (88) – 120 cm** **1.01166 (82) – 126 cm**	**122.69 cm** *(16691 pebbles)*

Likewise, the ***exact core model*** has been exploited to compare different ways of modeling the CFP in the inner region of the fuel pebbles. Three models mentioned above can be compared with each other: two regular lattices based on point-wise cross sections and an homogeneous model using 172-groups cross sections coming from a heterogeneous transport calculations performed previously (it is reminded that point-wise cross sections have been used everywhere else in the core simultaneously with this APOLLO2 library).

No real influence on the system reactivity has been observed according to the way employ to model the CFP inside the fuel pebbles. Moreover, the use of multi-group cross sections (provided by the transport code APOLLO2) only in that fuel region with point-wise cross sections elsewhere seems to be sufficient and confirms the TRIPOLI4 calculations performed with this approach on the HTTR benchmark[1 et 2]

4. 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-N1-04/07-D-1.1.0-1_1 - *Task Report*
  - HTR-N1-02/12-S-1.1.1-1_1
  - HTR-N1-03/06-S-1.1.3-1_1
- HTR-N1-04/07-D-1.2.0-1_1 - *Task Report*
  - HTR-N1-03/08-S-1.2.1-1_1
-
  - HTR-N1-04/07-S-1.3.1-1_1

REFERENCES

[1] **HTR-N-04/07-D-1.0.0-1_1.** Final summary report of the WP1 in HTR-N contract

[2] IAEA-TECDOC-1382, Volume 1 – *Evaluation of high temperature gas cooled reactor performance: Benchmark analysis related to initial testing of the HTTR and HTR-10* -. CRP-5, Nov. 2003

[3] IAEA-TECDOC-1198, Volume 1 – *Current status and future deveolpment of modular high temperature gas cooled reactor technology*. Fev. 2001