ANALYSIS OF THE EUROPEAN RESULTS ON THE HTTR's CORE PHYSICS BENCHMARKS

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ABSTRACT

Within the frame of the European contract HTR-N1 calculations are performed on the benchmark problems of the HTTR's start-up core physics experiments initially proposed by the IAEA in a Co-ordinated Research Programme. Three European partners, the FZJ in Germany, NRG and IRI in the Netherlands, and CEA in France, have joined this work package with the aim to validate their calculational methods. Pre-test and post-test calculational results, obtained by the partners, are compared with each other and with the experiment. Parts of the discrepancies between experiment and pre-test predictions are analysed and tackled by different treatments. In the case of the Monte Carlo code TRIPOLI4, used by CEA, the discrepancy between measurement and calculation at the first criticality is reduced to $\Delta k/k \sim 0.85$ %, when considering the revised data of the HTTR benchmark. In the case of the diffusion codes, this discrepancy is reduced to: $\Delta k/k \sim 0.8$ % (FZJ) and 2.7 or 1.8 % (CEA).

1. Introduction

In the frame of the European contract HTR-N1 a word package is devoted to the codes validation and methods improvements as far as the HTR modeling is concerned. Three partners are involved in this work package: FZJ in Germany, NRG and IRI in the Netherlands, and CEA in France. The HTTR's start-up core physics experiments are a good opportunity for the European partners to validate their calculational tools and methods. This paper provides an analysis of the pre-test and post-test calculations, performed in Europe on the benchmark problems of the HTTR's start-up core physics experiments: the number of fuel columns necessary to achieve the first criticality and the excess reactivity for 18, 24, and 30 fuel columns in the core, described in detail in [1].

2. Computational methods and nuclear data

The nuclear data libraries used by all 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 multigroup approximation (172 grps), provided by the SCALE4 code system, and the TRIPOLI4 code at CEA using pointwise cross sections everywhere in the core except in the fuel rod region where multigroup cross sections (172 grps) 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. Furthermore, it has to be mentioned that in the FZJ cell calculations no extra leakage term is used whereas in all other cell calculations a critical B^2_{crit}-search has been performed.

In the preliminary calculations the increased neutron streaming in the coolant channels and in the large holes of the core and the reflector is considered in the FZJ and NRG calculations. Later on, this enhanced neutron streaming is also taken into account in the post-test core calculations of CEA. The effect of the inhomogeneous distribution of the burnable poison (BP) in the axial direction is evaluated at NRG and FZJ, afterwards also in the post-test diffusion calculations of CEA.

3. Preliminary calculational results

Calculations [2,3] performed with the different code systems are presented on Table 1 together with the experimental results. The higher k_{eff}-values obtained by BOLD VENTURE and CRONOS are explained by the fact that the streaming effect is not considered and that the fuel blocks are homogenised in one region. This is also the case in CITATION, however this effect is counterbalanced by the absence of neutron leakage consideration in the cell calculations.

The relatively good agreement in the thin annular core assembly between both MC codes disappears in the fully loaded core. One reason can be that the P_1 approximation describing the interaction between neutrons and graphite has a higher impact on the neutron leakage at fully loaded core with its harder neutron spectrum than in the thin annular core configuration.

Table 1 Preliminary core calculations together with the experimental results

	CITATION	**PANTHER**	**B. VENT.**	**KENO**	**TRIPOLI**	**CRONOS**	**EXPER.**
	Diffusion 4 groups	Diffusion 2 groups	Diffusion 13 groups	M. Carlo 172 gr	M. Carlo 172 gr & pointwise	Diffusion 8 groups	
	3D triang.	3D hexag.	RZ	3D	3D	3D hexag.	
	1 reg/block	7 reg/block	6 rings			1 reg/block	
	finite diff.	finite elem.	finite diff.			finite elem.	
	6 mesh/bl.	7 mesh/bl.				24 mesh/bl	
30 col.	**1.1607** [@]	**1.1595**	***1.1885*** [#@]	**1.1600 *± 0.0005***	***1.1463*** [@] ***± 0.0009***	**1.1698** [@]	**1.1363 ± *(> 3.6 %)***
18 col.	**1.0254** [@]			**1.0240 *± 0.0005***	***1.0171*** [@] ***± 0.0009***	**1.0580** [@]	**subcrit.**

[@] *CR insertion considered Δk = 0.004* [#] *corrected for the BP effect from the KENO calculations*

4. Discussion of the preliminary results

The HTTR got critical with 19 fuel columns in the core with an excess reactivity of 1.5%. All preliminary calculations underestimated the number of fuel columns needed for the first criticality (diffusion calculations: 9, 16 fuel columns; Monte Carlo calculation: 17 fuel columns). As can be seen on Table 1, the discrepancy between the calculational results and the experiment at least ranges from Δk = 0.017 to 0.058 at 18 fuel columns loading, and from Δk = 0.01 to 0.052 at full core.

It is noteworthy that the observed discrepancies decreased with increasing number of fuel columns in the core. Due to the large experimental error at 30 fuel columns loading, the differences between the calculations and the experiment are within the error interval, whereas at the thin annular core assembly the discrepancies are significant. A reason for the latter circumstance can be the consideration of another than the actual boron impurity in the dummy fuel blocks and of residual air instead of helium in the graphite pores. Indeed, the impurity of one dummy fuel block has been re-measured by JAERI and revised data [4] have been recommended for the recalculation of the first criticality (HTTR-FC2).

Moreover, in the course of the studies the following reasons for the above mentioned discrepancies have been identified:

- the neglect of the detailed structure of the HTTR fuel block together with a non adequate modelling of the fuel and BP unit cells,

- the use of few group homogenized cross sections in the whole core diffusion calculation without neutron leakage in the transport calculations,
- a not adequate treatment of the axial self-shielding in the BP rods,
- an underestimation of the neutron streaming.

Therefore, the HTTR-FC2 has been a good opportunity to implement the new enhanced methods coming from the post-calculation analyses.

5. New calculational results

CITATION results

The discrepancy between measurement and the pre-test FZJ diffusion calculation amounts to $\Delta k = 0.0287$ at the first criticality (e.g. 19 fuel columns in the core) for a 4 group diffusion calculation without leakage feedback. At 30 fuel columns in the core the difference is with $\Delta k = 0.0261$ of the same order. Parts of the discrepancies between measurement and former calculations are tackled by considering: the exact asymmetric position of the B_4C-rods in the HTTR fuel block in the core diffusion calculation, together with an improved modelling of the unit cells, the use of many group constants or of few broad group constants including detailed leakage information in the diffusion calculation of the whole core in order to describe the core/reflector coupling accurately, the treatment of the axial self-shielding of the B_4C-rods by a 2-d discrete ordinates cell calculation, and the consideration of an enhanced neutron streaming, brought about by an adaptation of the diffusion constants to results of Monte Carlo calculations.

When applying these improvements [5] and taking the revised data of the HTTR, the first criticality was recalculated for 18 fuel columns, in case of fuel loading from the core periphery. The number of fuel columns, necessary to achieve the first criticality, increased by about 2 fuel columns compared to the former results, and the discrepancy between measurement and diffusion calculation was reduced from $\Delta k = 0.0287$ to $\Delta k = 0.0111$ at 19 fuel columns in the core.

The effective multiplication constants obtained in the pre-test and post-test calculations are given in Fig. 1 together with the experimental results. When summing up all post-test studies, the analysis yields the following effects at 18/19 fuel columns in the core compared to the pre-test results:

- when considering the detailed structure of the HTTR fuel block in the whole core calculation the multiplication factor decreases by about $\Delta k \approx 0.043$,
- the description of the detailed energy-dependence of the neutron flux adequately by a fine energy group structure increases the k_{eff}-value by about $\Delta k \approx 0.035$,
- when considering the axial heterogeneity of the BP by 2-d cell calculations, k_{eff} of the whole core calculation increases by about $\Delta k \approx 0.0068$,
- when treating the neutron streaming effect by modified diffusion constants on the basis of the Japanese Monte Carlo results, k_{eff} is reduced by about $\Delta k \approx 0.0075$,
- and when taking into account the revised HTTR benchmark data, the multiplication factor is reduced by about $\Delta k \approx 0.009$.

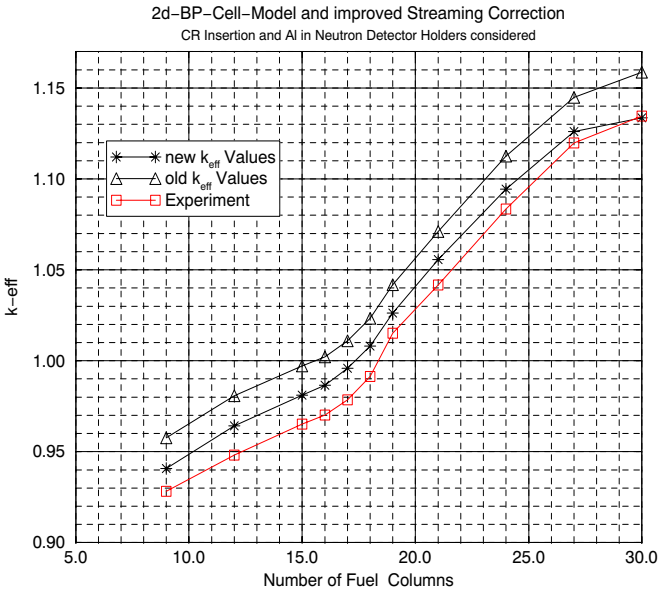

Fig.1: New and Old k_{eff}-Values of the Diffusion Calculations in Comparison with the Experiment

TRIPOLI4 and CRONOS2 results

Considering the new available data (HTTR-FC2), new Monte Carlo calculations have been performed with TRIPOLI4 for the 18, 19 and 30 columns configurations. The 18 columns case has been treated by taking into account or not the presence of the control rods slightly inserted in the upper part of the reflector ($\Delta k \sim 0.003$).

As far as the diffusion calculations are concerned, new developments carried out in APOLLO2 and CRONOS2 allow in future to take into account :

- the exact position of the BP in the fuel block by using new finite element mesh in the core model
- the streaming effect by generating anisotropic diffusion coefficients from the previous 2D-P_{ij} calculations

The use of the HTTR-FC2 data associated with a complete description of the axial heterogeneity of the BP has led to new core diffusion calculation results. This has been done for six different energy structures (2, 4, 6, 8, 13 and 20 groups) in CRONOS2. Finally, the Benoist method used for the treatment of the neutron streaming might not be applicable in the large channels of the control rod graph blocks (18 columns) and underestimates this effect. Furthermore, two other analytical models (Benoist) have been tested on a control rod block alone and validated by MC calculation. This led to better results on the whole core.

The final results are partially gathered in the Figures below. Fig. 2 illustrates, with 8 energy groups, the impact of the different model assumptions on the reactivity as a function of the number of fuel columns. Fig. 3 shows a streaming effect ranging from 2.25 % in the 18 columns core configuration to 1.8 % in the full core configuration. These results highlight also the importance of the used leakage model for evaluating the neutron streaming in the control rods graphite blocks. Indeed, the first model gave some values varying from 1.8 % to 1.5 %.

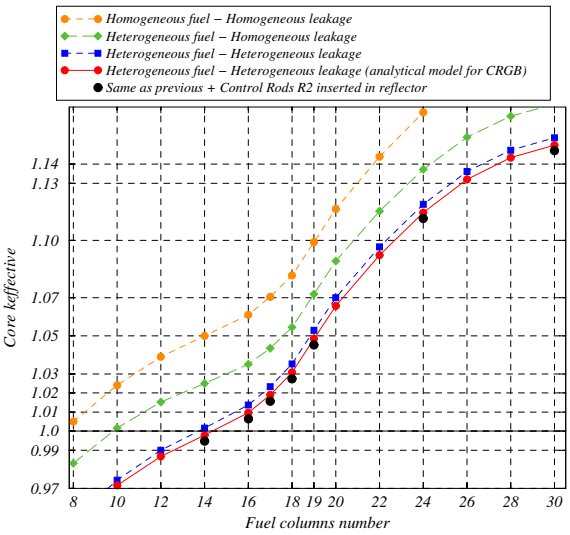

Fig 2. k_{eff}-values obtained by different core models

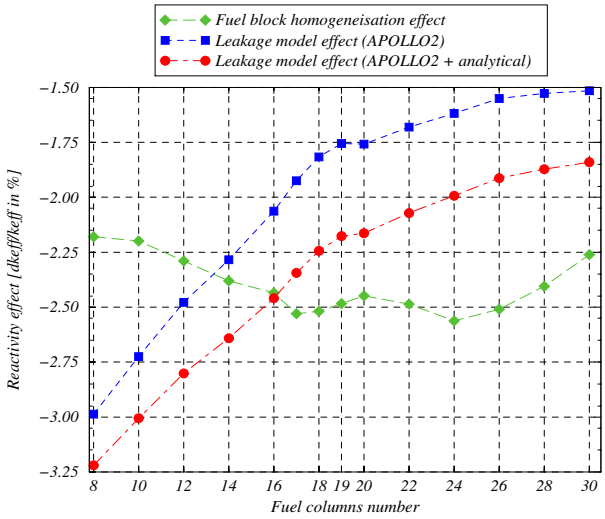

Fig 3. Neutron streaming and fuel block homogenisation effect

It is noticeable that the number of fuel columns needed to achieve criticality increases by about 7 or 8 in comparison with the former results (Table 1). At first criticality, a discrepancy remains between the diffusion and the Monte Carlo calculations ($0.9\ \% < \Delta k/k < 1.7\ \%$). This underscores the limits of a method based on a cross section homogenisation from a fundamental mode calculation (infinite medium) that is barely pertinent for the 18 columns core configuration. The actual environment (reflector blocks) should be considered and should take place instead of the white boundary condition in the 2D APOLLO-2 transport calculations, before homogenising and collapsing locally the cross sections inside the fuel elements.

6. Final results and conclusion

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 $\Delta k/ \sim 0.85$ %, when considering the revised data of the HTTR benchmark. As to the diffusion codes, this discrepancy is now reduced to $\Delta k/k \sim 0.8$ %(FZJ) and ~ 2.75 (1.78) %(CEA), when taking account of the improved treatments and the revised data.

Table 2 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 gr.)	
	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 (1.1362)** [2)]	**1.1363 ± (> *3.6 %*)**
24 col.	**1.0944** [1)]	**-**	**1.1096 (1.1000)** [2)]	**1.0834 ± (> *2 %*)**
19 col.	**1.0263** [1)]	**1.02692** [2)] ***± 0.00043***	**1.0432 (1.0351)** [2)]	**1.0152 ± ?**
18 col.	**1.0080** [1)]	**1.00855** [2)] ***± 0.00090***	**1.0275 (1.0178)** [2)]	**subcritical**

[1)] *CR inserted considered $\Delta k = 0.004$ and detector impact included $\Delta k = 0.002$*
[2)] *detector impact included $\Delta k = 0.002$*

All calculational results obtained for the fully loaded core configuration agree well with each other and with the experiment, moreover when taking into account the experimental uncertainties. Furthermore, it is seen that there is an excellent agreement between the diffusion CITATION and Monte Carlo TRIPOLI calculational results. Altogether it turns out that the following procedures seem to be necessary for a better approach to the experimental results:

- detailed heterogeneity of the BP- 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 (CEA) transport cell calculations in order to describe the core/reflector coupling accurately,
- consideration of the axially heterogeneous distribution of the BP 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).

7. References

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