EUROPEAN COMMISSION
5th EURATOM FRAMEWORK PROGRAMME 1998-2002
KEY ACTION : NUCLEAR FISSION

HTR-N

High-Temperature Reactor Physics and Fuel Cycle Studies

CONTRACT N°
FIKI-CT-2000-00020

Work Package 1

Analyses of the European results on the HTTR's startup core physics experiments

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Dissemination level : RE
Document Number: HTR-N-00/12-D-1.1.2.
2 december 2000

NUCLEAR DATA

As for the pointwise cross section used in the Monte Carlo calculations, the 123 and 172-group cross section (XS) libraries come from the JEF2.2 evaluated nuclear data file and treated by NJOY. For the present calculations, the existing multi-group libraries have been used without specific reprocessing with NJOY. Therefore, the multi-group cross sections are weighted by classical Maxwell+1/E+fission spectrum.

CROSS SECTION GENERATION

The general methods and assumptions used to model fuel and block elements and to generate the cross sections for the core calculations are gathered in Table 1.

As far as the core diffusion model are concerned, the streaming effect is treated by the uses of anisotropic diffusion coefficients (Dz ≠ Dr). These diffusion coefficients can be estimated by the way of an heterogeneous neutron leakage model included in the transport code as it is the case for WINS-7. The homogenised fuel block regions contain therefore anisotropic diffusion coefficients taking into account the presence of large coolant channels or control rod guides which increases neutron streaming in the axial direction. Not available in the SCALE-4 system, the heterogeneous leakage model of APOLLO-2 does not still run today with the 2D-generalised-geometry module used for the HTTR calculations. Consequently, the group constants provided to CRONOS-2 and BOLD VENTURE have only homogeneous diffusion coefficients. Finally, The MARCOPOLO code has been used to adjust the homogeneous diffusion coefficients calculated by TOTMOS and thus given to CITATION in form of correction factors.

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Table 1

<table>
<tr><th>WIMS 7</th><th colspan="2">SCALE 4</th><th colspan="2">APOLLO 2</th><th colspan="2">NITAWL/ TOTMOS</th></tr>
<tr><td></td><td colspan="2">172 gr
<u>1D spherical cell</u>
Self shielding + Dancoff</td><td colspan="2"></td><td colspan="2">123 gr
<u>1D spherical cell</u>
Self shielding + Dancoff</td></tr>
<tr><td>69 gr - Pij
<u>1D cyl. fuel cell</u>
Double hete.
<u>Self shielding</u>
B² crit.</td><td colspan="2">172 gr – Pij
<u>1D cyl. fuel cell</u>

B² crit.</td><td colspan="2">172 gr - Pij
<u>1D cyl. fuel cell</u>
Double hete.
<u>Self shielding</u>
B² crit.</td><td>123 gr - Pij
<u>1D cyl. fuel cell</u>

B² crit.</td><td>123 gr - Pij
<u>1D cyl. BP cell</u>

B² crit.</td></tr>
<tr><td>16 gr - Pij
<u>2D ‘multi-pin’</u>
B² crit.
hete. leakage
no equivalence#</td><td rowspan="3"></td><td></td><td>172 gr - Pij
<u>2D</u>
B² crit.
homo. leakage
no equivalence#</td><td rowspan="3"></td><td rowspan="3"></td><td></td></tr>
<tr><td></td><td>172-gr cell averaged
σ_{172gr}(isot)</td><td rowspan="2"></td><td rowspan="2"></td><td>123-gr cell averaged
$\sigma_{123gr}(^{10}B)$ adjusted from
S_n R-Z BP cell.</td></tr>
<tr><td></td><td>172 gr – Pij
1D cyl. core</td></tr>
<tr><td>2-gr <u>block region averaged</u>
Σ_{2gr}(isot) for PANTHER</td><td>172-gr <u>fuel averaged</u>
σ_{172gr}(isot) for KENO</td><td>13-gr <u>core reg. averaged</u>
σ_{13gr}(isot) for BOLD VENT.</td><td>8-gr <u>block averaged</u>
Σ_{8gr}(isot) for CRONOS</td><td>172-gr <u>fuel averaged</u>
σ_{172gr}(isot) for TRIPOLI</td><td colspan="2">4-gr <u>cell averaged</u>
σ_{4gr}(isot) for CITATION</td></tr>
</table>

tr. 16gr -> diff. 2gr and tr 172 gr -> diff. 8 gr

CORE CALCULATIONS

Calculations performed with the different codes systems are presented below. Four diffusion codes have been used. The KENO calculations can be considered as a 3D transport calculations whereas the TRIPOLI-4 runs are simultaneously a Monte Carlo calculation with pointwise cross sections and a 172 gr transport calculation on the fuel compact region.

Table 2

	CITATION	PANTHER	B. VENT.	KENO	TRIPOLI	CRONOS
	Diff. 4 gr 3D triang. 6 reg/block finite diff. 6 mesh/bl.	Diff. 2 gr 3D hexag. 7 reg/block finite elem. 7 mesh/bl.	Diff. 13 gr RZ 6 rings finite diff.	MC 172 gr 3D	MC 172 gr & pointwise 3D	Diff. 8 gr 3D hexag. 1 reg/block finite elem. 24 mesh/bl
30 col.	**1.1607**	**1.1595**	***1.1925*#**	**1.1600** **± 0.0005**	**1.1503** **± 0.0009**	**1.1738**
18 col.	**1.0254**			**1.0240** **± 0.0005**	**1.0211** **± 0.0009**	**1.0620**

#*corrected for the BP effect from the KENO calculations*

The experiments give the following values for both core configurations :

> Δk/k = 12 ± 3.3 % for the first one and **barely subcritical** for the simple core arrangement. The first value leads to a multiplication factor of **1.1363** but with an important uncertainty that must be emphasized. In these conditions, the differences between calculation and experiment are comparable and correspond to an overestimation of the core reactivity ranges from **Δk = 0.015 to 0.025** for the fully loaded core and **Δk ≥ 0.020 to 0.025** near the first criticality.

Due to the large experimental uncertainty on the full-core excess reactivity, the following discussions will be first focus on the explanations of the discrepancies between diffusion and Monte Carlo calculations. Moreover, new data are now available to re-calculate the HTTR-FC and should permit to get nearer to the experiment.

Comments

First of all, it seems to be important to note that only the CITATION given values include the control rods insertion in the top of the side reflector for which a reactivity effect of Δk = 0.004 has been considered.

The higher discrepancies of the values evaluated by both BOLD VENTURE and CRONOS-2 are explained by the fact that the streaming effect is not taken into account here. Moreover, as it will be noticed below the rough axial representation of the boron pin in CRONOS-2 compensates the streaming effect which is not modelised.

The relatively good accordance (Δk < 0.003) in the simple core configuration between both MC codes disappears in the fully loaded core configuration (Δk # 0.01). One explication could be that the P1 approximation describing interaction between neutrons

and the graphite would have a higher impact on the neutron leakage in case of the harder neutron spectrum of the fully loaded core.

AXIAL HOMOGENISATION OF THE BURNABLE POISON (BP)

The BPs in the fuel blocks present an axial heterogeneity. The B_4C pellets are stacked with graphite disks put between them and can be modelled explicitly or not during the cross section generation process. In order to evaluate the impact of these model assumptions, two comparisons have been done on core calculations performed with CITATION and TRIPOLI-4.

In the Monte Carlo calculation only the BP rods have been homogenised (B_4C-C) in the 3D detailed geometry and compared to the reference case given above (Table 2). As far as the diffusion calculation is concerned, it is in course of the cross section generation process that the BP adjustment, based on the Sn-RZ cell calculation, has not been considered (see Table 1). The cell averaged cross sections with and without BP adjustment have been then used in the core calculation.

Table 3

	reactivity effect - $\Delta k_\infty/k_{hete}$ (pcm#)	
	TRIPOLI-4	**CITATION**
30 columns	**0.0220** (2224 pcm)	**0.0226** (2292 pcm)
18 columns	**0.0145** (1460 pcm)	**0.0198** (2000 pcm)

$10^5.ln(k_1/k_2)$

The spatial self-shielding effect of the B_4C is clearly highlighted. The homogenisation of the BP rods leads to an overestimation of the boron absorption which is amplified with the number of fuel blocks loaded in the core although the neutron spectrum is harder. It is noteworthy that this effect is less emphasis by the diffusion calculation in the 18-columns related case for which it is more difficult to get flux weighted cross sections well representative of the core conditions.

Although less important it is interesting to note that if this effect is applied to the multiplication factor evaluated by CRONOS-2 model (Table 2) for which the BP are homogeneous, a $k_{eff} = 1.1996$ is obtained. This value is very close to the one calculated by BOLD VENTURE.

Besides, this overestimation has also been underscored in the spectrum calculations. The effect on the infinite multiplication factor ranges from 0.015 to 0.033 depending of the fuel block enrichment and is smaller for harder neutron spectrum (higher enrichment). The Δk values calculated with DORT on a BP cell (Table 4) lead to comparable effect than those obtained with TRIPOLI-4 on a 3D/2D fuel block geometry (Table 5).

Table 4

R-Z BP cell with DORT	Fuel block 993120 (enrichment 9.9 %)	Fuel block 343320 (enrichment 3.4 %)
$\Delta k_\infty / k_{hete}$	**0.0155**	**0.0335**

Table 5

Fuel block 993120 with TRIPOLI-4	3D hete. BP	2D homog. BP
k_∞ ($B^2 = 0$)	1.4187 ± 0.0005	1.3994
$\Delta k_\infty / k_{hete}$		**0.0136**
$\Delta(\Sigma_a \Phi)_{BP}$		*+ 11.1 %*

The comparison of the reaction rates between both calculations displayed in Table 5 lead to an overestimation greater than 10 % of the total absorption rate in the BP rods but to comparable absorption rates in the fuel compact.

FUEL BLOCK HOMOGENISATION

Two consequences due to the fuel element homogenisation in the core diffusion calculations can be identified:

- this can lead to an overestimation of the core reactivity by neglecting the neutron streaming in the cylindrical and annular holes in the core regions if the diffusion coefficients have not been adjusted or calculated precisely.
- the anomalies in the blocks like BP and their positions smeared over the entire block does not allow good representation of local absorptions. A solution which consist in considering several regions in the blocks with different group constants allows to take into account block heterogeneities but often requires equivalence factors to respect either the flux or the absorption rates between fine multigroup transport calculations on the heterogeneous block and broad group diffusion calculations with several homogenised regions per blocks.

Radial homogenisation effect

This last point has been evaluated with TRIPOLO-4 and CRONOS-2 in a 2D radial core configuration (without axial leakage). In this case the streaming effect and the BP axial homogenisation are then not considered. Therefore, the results given in Table 6 point towards the radial homogenisation of each block in one region a piece.

For the homogenised case, the 2D-diffusion core calculations give results close to those obtained by the Monte Carlo where the fuel blocks are represented by homogeneous 172 group cross sections.

Table 6

	k_{eff}(2D) no axial leakage			$\Delta k/k_{hete}$
	TRIPOLI-4 hete.	**TRIPOLI-4 homo.**	**CRONOS-2 homo.**	**TRIPOLI-4**
30 columns	1.28837 ± 0.00069	1.31985 ± 0.00063	*1.32675*	**0.0244**
18 columns	1.14040 ± 0.00087	1.18554 ± 0.00075	*1.18630*	**0.0396**

The reduction of the homogenisation effect for the fully loaded core is essentially due to the hardening spectrum observed in this case. This reduce the impact of the underestimation of the BP absorption and moreover, the neutron spectrum becomes closer to the one existing in the 2D transport calculations carried out on the blocks with a white boundary condition.

In the 18 columns core configuration, the neutron spectrum seen by the BP during the 2D transport calculations is very different from those observed in the core conditions. A next step in the calculations to explain the discrepancies with the experiment will have to take into account surrounding regions for the fuel block under study as it has been done with WINS-7. However, this have the disadvantage to increase the complexity of the transport calculations and to multiply the number of cases to be treated.

Streaming effect

All the obtained values for tentatively quantifying this effect are gathered in Table 7. Considering that the CRONOS-2 model does not take into account the streaming effect, the axial heterogeneous composition of the BP and the heterogeneities of the blocks, the streaming effect can be deduced from the last two points which have been quantified above.

Besides, additional calculations with CITATION have been performed without the streaming correction factors provided by MARCOPOLO. This permit to have an estimation of the streaming effect alone.

Finally, a comparison between the detailed core model of KENO and an homogenised core model of KENO and BOLD VENTURE has been carried out on a core configuration without BP. In this condition, the problem of the BP axial homogenisation is withdrawn and the differences on the obtained values provide indication on the streaming effect.

It appears that the $\Delta k/k_{st}$ evaluated from KENO and BOLD VENTURE can not be attributed to the streaming effect only. Homogenisation effect as described in the previous section obviously take place here. A 172 gr 3D transport calculations on the fully detailed core is compared to an 13 gr R-Z diffusion calculations with 6 homogenised rings. The R-Z and diffusion related assumptions have a small impact if it is compared to the $\Delta k/k_{st}$ obtained with a KENO det./KENO homog. assessments on a simplified core. Therefore, cross sections provided by the spectrum calculations and the homogenisation of the different kind of blocks in the rings should explain the above values.

Table 7

	$\Delta k/k_{st}$ - 30 columns	$\Delta k/k_{st}$ - 18 columns
CITATION with and without streaming	**0.0132**	**0.0176**
KENO *simplified core <e=5.2%>, no BP* detailed and homogenised model	**0.0256**	**-**
KENO – BOLD VENTURE *no BP* detailed and R-Z homogenised model	**0.0280**	**-**
Estimated values deduced from TRIPOLI-4 / CRONOS-2 calculations	***0.0152***	***0.0185***

If it assumes that the 0.0256 value obtained by KENO correspond to both the streaming and homogenisation effects and taking into account the order of magnitude of the streaming effect given by CITATION and TRIPOLI-4, the homogenisation effect would be near 0.01. This value is smaller than the one given in Table 6 (0.0244) and should be explain by the absence of BP in the KENO calculations.

PRELIMINARY CONSIDERATIONS ON THE CORE IMPURITIES

A simple exercise has been carried out with TRIPOLI-4 on the thin annular core configuration in order to estimate the impact of the graphite impurities on the reactivity. The impurity rate of only the 12 dummy fuel blocks at the centre of the core has been multiply by 1.5 and 2. As shown in the table below the latest value might lead to a barely critical state.

Table 8

Dummy fuel block Impurity:	k_{eff}
Benchmark data: I_{ref}	**1.02110±0.00090**
150 % of I_{ref}	**1.01350±0.00090**
200 % of I_{ref}	**1.00070±0.00090**

Seeing that these impurity rates seem to be not realistic but that only 12 central blocks were considered this exercise might explain the discrepancies with the experiments. Indeed, new data are available considering new graphite impurities and the presence of air (N, O) in the graphite porosities of the fuel blocks, CR guide blocks, reflector and matrix of the fuel compact. According to the absorption cross section and the concentration of N^{14} in the pores of the graphite, the presence of air in the core amounts to saying that 1 ppm of natural boron equivalent will be added in each component of the core.

These considerations will have to be confirmed by further calculations.