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HTTR CRITICALITY, PHYSICAL PARAMETERS CALCULATIONS AND EXPERIMENTAL RESULTS

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Abstract

Both NRG (merger of the former nuclear units of ECN and KEMA) and IRI take part in the benchmark of start-up core physics of the High Temperature Engineering Test Reactor HTTR, which is part of the IAEA Co-ordinated Program “Evaluation of HTGR Performance". To compare the performance of the SCALE based IRI code package with that of the WIMS/PANTHER code package of NRG, a calculational intercomparison has been done. This report first describes the NRG and IRI efforts in the first Benchmark (Phase 1) using the Monte Carlo code KENO Va (3-D) and the diffusion theory codes BOLD VENTURE (2-D) and PANTER (3-D). In the second phase of the Benchmark, only KENO calculations are performed, for the scram reactivities of the core and reflector control rods and the isothermal temperature coefficients are given for phase 2. NRG /IRI also participated in the start-up measurement of reactivity and reactor noise measurements. Results of the calculations and the experimental effort will be summarised in this paper.

1. Introduction

The safety demonstration test of the HTTR (Saito et.al., 1994) will be carried out for the safety features of a next generation of HTGR's. The HTTR is designed for 30 MW thermal power and consists of a reactor core and main, auxiliary and vessel-cooling systems. The active reactor core with height of 2.9 m and equivalent diameter of 2.3 m consists of 30 prismatic fuel columns, which carry the fuel compacts with theUO_2 loaded coated fuel particles. The core is positioned in the reactor pressure vessel with height of 13.2 m and diameter of 5.5 m. The inlet coolant temperature of the reactor at full power operation is 395 ^{o}C, the outlet coolant temperature is 850/950 ^{o}C. The reactor achieved to first criticality on November 10, 1998. With this reactor nuclear heat will be used for hydrogen production by means of steam reforming. After reaching to first criticality with 19 fuel columns loaded, successive fuel loadings were performed until the full core loading was achieved. In the mean time, two international physics benchmarks were established by the IAEA organisation under the CRP-5 (Nakano et. al., 1998 and Yamashita et. al., 1999a)

The first participation for the calculation of the first criticality in Phase 1 will be summarised in the section 2. The second benchmark results of Phase 2 will be summarised in the section 3. In section 4, some results of the reactivity measurements and the reactor noise measurements at very low power will be given. In the section 5, conclusions of the calculations and the experiments will be given.

2. Results of the HTTR Startup-Core Benchmark Phase 1

First the generation of cross sections will be described for the Monte Carlo calculations and for calculations with deterministic codes by as well the SCALE as the WIMS packages, which are both produced from JEF-2.2 basic nuclear data files. Because the configuration of the core is quite complicated with the total 12 different uranium enrichments, NRG and IRI decided first to analyse a simpler configuration also, to compare cross sections and the core model. In this simpler configuration only 5.2 % enriched uranium is used for all fuel blocks in the reactor (a representative average for the reactor fuel). Subsequently, results of the analysis (Wallerbos et.al.,1998a, 1998b and de Haas et al.,1998) of the simple and complex core configuration with the multigroup Monte Carlo code Keno Va (3-D) and the diffusion theory codes BOLD VENTURE (2 D) and PANTER (3 D) are presented for Phase 1 of the Benchmark.

In KENO, only the coated fuel particles (CFP's) in the fuel compacts are homogenised with the graphite matrix of the fuel compacts; all other reactor components can be modelled explicitly. As the fuel also contains the only two resonant nuclides (^{235}U and ^{238}U) present in the core model, the only problem is the generation of cross sections for the homogenised fuel compacts.

1. First only the coated fuel particles inside a fuel rod are considered. An infinite close-packed hexagonal CFP lattice is calculated by the SCALE modules BONAMI, NITAWL and XSDRNPM. XSDRNPM is run in spherical geometry for a white boundary elementary cell of the CFP lattice. This elementary cell contains two regions: a sphere which contains the fuel kernel of UO_2 surrounded by the homogenised mixture of the coating layers and graphite matrix in the fuel compact. The matrix graphite contains some natural boron to represent impurities in the graphite. A cell-averaged weighted library, WGH(1), is produced which takes the self-shielding of the fuel in the CFP's into account.
2. An infinite fuel-rod lattice is treated by BONAMI and NITAWL to obtain working library WRK(1). The unit cell with cylinder geometry has three regions. The innermost region is a channel filled with helium surrounded by a cylinder with the fuel. The outermost region surrounding the fuel contains fuel block graphite. A triangular lattice is assumed with a pitch of 6.267 cm, consistent with 1/33rd block for the 33-rods fuel block. This step is required because it provides the unweighted data for the materials outside the fuel region. The overall Dancoff factor for the core has been deduced from the Dancoff factors for a lattice of CFP's in a fuel compact and for a lattice of fuel rods in a fuel block (Wallerbos et.al.,1998a).
3. All fuel-region materials from the weighted library WGH(1) are merged with the structural materials from WRK(1). The resulting library is called WRK(2).
4. XSDRNPM is run with working library WRK(2) for the unit cell of the infinite fuel-rod lattice. This unit cell of cylindrical geometry has five radial zones: 1. Channel with helium (r=0.5 cm). 2. Fuel zone (r=1.3 cm). 3. Graphite sleeve of fuel rod (r=1.7 cm). 4. Fuel hole in fuel block filled with helium (r=2.05 cm). 5. Fuel block the radius is of this zone is 3.29 cm (1/33rd fuel

block). XSDRNPM is run with a buckling search option to get a critical system. The weighted library WGH(2) with **zone**-averaged cross sections is produced.

5. In order to obtain a working library for KENO, the cross sections for the nuclides inside the fuel compact from WGH(2) are merged with the cross sections for all nuclides in the other components (He, C, ^{10}B, and ^{11}B) from WRK(1). The resulting library is denoted as WRK(3).

No group collapsing is done in any of these steps. All libraries contain cross section data for 172 energy groups! A simpler scheme would have been possible if no comparison had to be made for two-groups cross sections.

For the use in BOLD VENTURE a similar procedure has been used
The first three steps are identical to the procedure for KENO. The fourth step is similar, but now a **cell** weighting is performed instead of a **zone** weighting. Subsequent steps are new.

1. Unweighted cross sections for the materials outside the fuel blocks (i.e. inside the control rod guide blocks and reflector) have to be added to WGH(2). These unweighted cross sections of C, ^{10}B, and ^{11}B, were taken from WRK(1). The resulting library is called WRK(3).
2. XSDRNPM is run with library WRK(3) for a 1D-model of the reactor. This model contains six radial zones. The first five represent the five rings of the core region, the outermost zone represents the permanent reflector. The radii of the zones were calculated to be 19.01 cm, 50.29 cm, 82.85 cm, 115.61 cm, 148.44 cm, and 214.98 cm. With these radii, the area of the rings is equivalent to the true area of the columns. The material within each zone is completely homogenised. Note that the burnable poison rods (BP) are not taken into account. XSDRNPM is run with a buckling search option and with zone weighting, producing weighted library WGH(3). For BOLD VENTURE the groups were condensed to 13 broad groups. For comparison purposes further condensing yielded 2 broad groups cross sections.

Cross sections for the reactor code PANTHER have been generated by means of the code suite WIMS-7B. Apart from service modules for group condensing and material homogenisation, two collision probability modules were used to calculate the flux weighted cross sections of the fuel cell (PROCOL) and for the fuel blocks or assemblies, control guide blocks and reflector blocks (PIJ).
In the WIMS-suite a cell module PROCOL, based on collision probabilities, exists to calculate fluxes in systems with spherical grains packed in a matrix with an annular geometry.
A cell of the same layout and dimensions as used for the KENO cross section generation step 4 has been modelled. Using this model, flux weighted cross sections are obtained for the compact materials in the 69 neutron energy groups structure of the library. These cross sections were condensed to 16 neutron energy groups for subsequent use in the WIMS assembly module PIJ, which calculates collision probabilities in multi-pin assembly systems.

The spectrum in the centre of the inner gas channel in the compact with 5.2 w% enrichment compares very good with the spectrum as obtained with the KENO cross sections. Differences are only due to the resolution of the spectrum with the number of energy groups used in the calculations (KENO: 172 vs. WIMS: 69). Good agreement also for the calculated neutron multiplication factors: $k_{inf} = 1.499$ for the 'KENO'-cell and $k_{inf} = 1.493$ for the 'PROCOL'-cell.

For modelling in PIJ the fuel assembly has been adapted in the following way that four layers in the assembly can be created (Fig. 1):

1. First layer of 15 cm height with compacts, fuel handling hole (FHH) and BP pellets,
2. Second layer of 10 cm with compacts, FHH and the graphite disks at the BP position,
3. Third layer of 25 cm with compacts, graphite for FHH and with BP pellets,
4. Fourth layer of remaining 8 cm with a mix of the remains of compacts, graphite, void at the fuel positions and graphite at the FHH and BP positions.

Void has been modelled in the empty BP insertion leg.

For each layer a model of the fuel assembly has been laid out in which the hexagonal perimeter has been replaced by an equivalent circle (radius 19.01 cm). Within this circle the fuel positions (comprising: inner gas space, compact, sleeve and outer gas space), FHH and BP insertion holes are modelled at the exact positions and filled with the materials in conformance.
This circle in turn is surrounded by another circle (radius 38.01 cm), divided into 12 segments, to accommodate the matching surrounding materials for the fuel assembly under study.
It makes a total of 206 material regions per assembly layer.

To reduce the number of materials, the PIJ model is finally divided into seven regions: one central region comprising the FHH position and the six inner fuel positions, and the six surrounding segments. Materials within a region are homogenised or smeared to one material. Finally the seven materials for the four layers are smeared, according to their height, to seven final materials for one assembly having flux weighted cross sections in 16 neutron energy groups.
The procedure for the control guide blocks and reflector blocks is similar; also divided into seven regions but with only two layers, with and without FHH.

Advantage of the sub-division in seven regions is that the anomalies in a block, like BP stacks, absent fuel pins, control guide holes, control rods, etc. are confined to only one region a piece and are not smeared over the entire block. This allows for more pronounced local absorption and/or streaming, which form major problems for modelling this kind of reactor cores.
For all 48 different block configurations (enrichments, block types, surroundings, etc.) two runs with PIJ were done; first a run without control rods (unrodded) and a second run with control rod material modelled in the control guide holes and using rodded material in that sector of the surrounding where present (rodded).
Afterward all cross sections were condensed to two energy groups (E_{th} = 2.1 eV) and organised in such a way that it can be used in the reactor code PANTHER, leading to 336 different materials in as well a rodded state as an unrodded state.
By making use of the modules PROCOL and PIJ the double heterogeneity formed by the CFP's and the fuel rods has been modelled explicitly and therefore no Dancoff factor has to be introduced.

The KENO model is a very detailed model of the HTTR in which practically all components are modelled explicitly, with the following exceptions:

1 As mentioned before, the coated fuel particles were homogenised with the graphite matrix of the fuel compacts.
2 It is not possible to model hexagonal blocks in KENO-Va. Therefore, the permanent reflector was approximated by a cylinder of 214.98 cm radius which preserves the volume of the actual reflector. Furthermore, the hexagonal blocks in the core and in the replaceable reflector were represented by cylinders of 36 cm diameter (the distance between the parallel faces of the

blocks). These cylinders (which contain all fuel rods and the two burnable poison rods or all coolant channels) were placed in a large cylinder of graphite with a radius of 162.9 cm (Fig. 1).

In the BOLD VENTURE model the HTTR is represented by an R-Z model. It contains six zones in the radial direction, and nine in the axial direction, one for each layer. The six radial zones are:

1. the central control rod guide column (column A)
2. the first fuel zone (the six B columns)
3. the second fuel zone (the 12 C columns: 6 fuel columns and 6 control rod columns)
4. the third and fourth fuel zone (the 18 D columns)
5. the replaceable reflector (the 24 E columns)
6. the permanent reflector

The height of each layer is 58 cm, except layer 9 (42.9 cm). The radii of the zones are: 19.01, 50.29, 82.85, 115.61, 148.44 and 214.98 cm. Calculations were performed with a 2 cm mesh, both in axial as radial direction and the BP rods were simulated by adding boron to the radial zones B, C and D to such an extend that a reactivity change, as determined by auxilary KENO calculations, was reached.

For PANTHER a 3-D model has been developed in a hexagonal representation, taking a cluster of seven sub hexes (size: 13.68 cm flat-to-flat) per hexagonal reactor assembly position in the radial direction and 5 layers per assembly in the axial direction. This leads to 937 radial reactor channels with an equivalent radius of 220 cm and 45 axial layers of 11.6 cm.
Control rods, those left partially inserted in the E-column ring, reached only till the bottom level of the upper block (464 cm level).
Materials defined and prepared in the WIMS data generation phase has been laid down according to proper compositions and orientations of the reactor assembly blocks in the reactor. For the simple core all enrichments were set at 5.2 w%.
In PANTHER the assemblies which carry control rods are represented by two sets of nuclear data: one set for the part where is no control rod inserted (unrodded) and a set for the rodded part. The control rod insertion depth for a certain control rod bank determines whether PANTHER uses the set for the rodded material or for the unrodded material in a particular mesh, thus enabling to drive a control rod.
The results of the calculations by the different codes are presented in Table 1. Good agreement can be found between the KENO and PANTHER results, the higher k_{eff} values for BOLD VENTURE can be attributed to neutron streaming in the control rod guiding holes
.

Table 1. Comparison of the results.

	KENO	BOLD-VENTURE	PANTHER	Measured
k_{eff} simple core	1.1278 ± 0.0005	1.1592	1.1251	
k_{eff} fully loaded core				
- rods withdrawn	1.1584 ± 0.0005	1.1974	1.1595	
- rods inserted	0.6983 ± 0.0005		0.7510	0.685 ±0.010
critical insertion				
- above bottom core	170.5 cm		161.5 cm	178.9 cm

3. Results of the HTTR Start-up-Core Benchmark Phase 2

The second benchmark of the HTTR core physics (Phase 2), defined by JAERI (Yamashita et.al.,1999b), were also calculated by using the Monte-Carlo code KENO-Va (V4.3) for a fully loaded core with 30 fuel elements and are presented in the Working Material of the IAEA meeting (CRP-5, 1999 and Türkcan et.al.,1999). We will summarise the results shortly.

In Phase 2 the following answers were requested by the organisers:
- Scram reactivities (control rod worth) for the control rods at critical position and after a scram of the reflector control rods (HTTR-SR) and after a scram with all the control rods (HTTR-SA), both at a temperature of 300K.
- Isothermal temperature coefficients for a fully loaded core from 280K to 480K in six temperature steps (HTTR-TC). Where the control rod settings (C, R1 and R2) have slightly different settings due to a temperature elevation and the critical insertion of the control rods C, R1 and R2, (R3 stays fully out) at 480K.

For the new benchmark calculations, new cross-sections were prepared for seven different temperatures using the aforementioned procedure. The resulting cross section libraries contain data for 172 neutron energy groups. The geometry input for KENO is revised to be able to calculate the questions of the benchmark. The KENO model for a critical reactor and with all control-rods inserted is shown in Fig. 1.
The results of the benchmark-phase 2 will be summarised.
The scram reactivity of control rods ($\Delta k/k$) is defined by:

$$r_R = \frac{k_{Crit} - k_{RCR-in}}{k_{Crit} . k_{RCR-in}}$$

With: $k_{Crit.}$: Effective multiplication factor at critical CR position
and k_{RCR-in}: Effective multiplication factor at CR position after scram.

For the scram reactivity for two different scram conditions as given in Table 2, the calculated and measured scram reactivities (Fujimoto et.al.,1999) are given in Table 2 as well.

Table 2. Scram reactivities

CR Group	Critical position (mm) HTTR-Crit	Position after scram (mm) HTTR-SR	Position after scram (mm) HTTR-SA
C	1789	1789	-41
R1	1789	1789	-41
R2	1789	-41	-41
R3	Full out	-41	-41
k_{eff} (average)	1.0093 ± 0.000	0.9178 ± 0.0005	0.6809 ± 0.0005
ρ_{calc}		0.0988 ± 0.0007	0.4778 ± 0.0007
ρ_{meas}		0.120 ± 0.012	0.46 ± 0.04

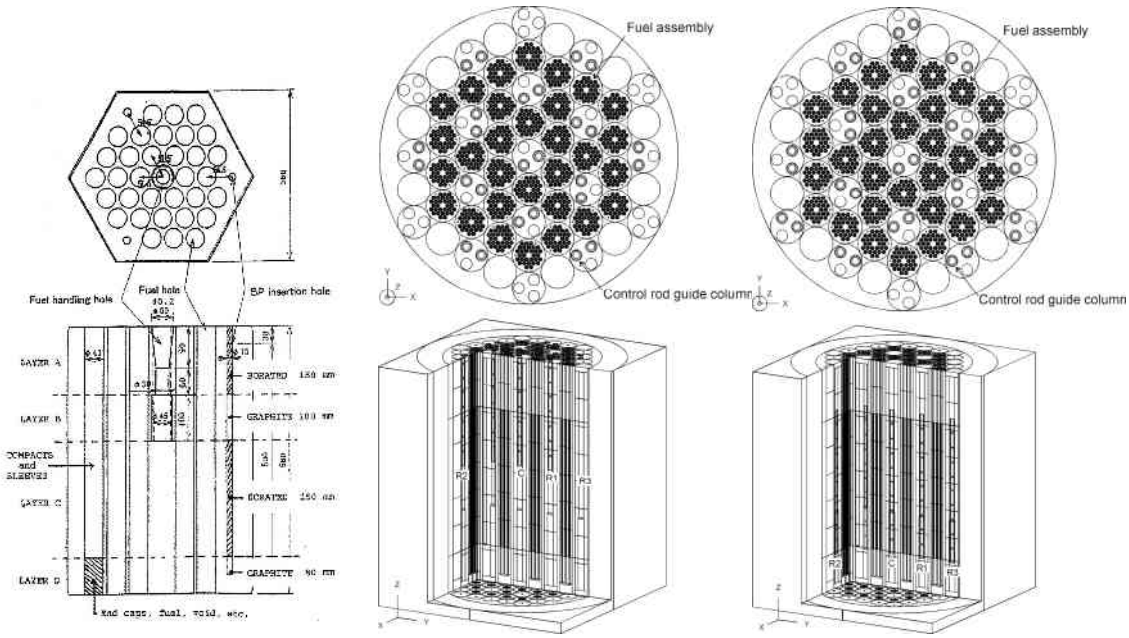

Figure 1: The design of the fuel assembly (left), the KENO model for the critical reactor (middle) and the KENO model for scram with all the control rods (C, R1, R2, and R3) (right).

In the second question of the benchmark, the isothermal temperature coefficients (HTTR-TC) for a fully loaded core between temperatures 280K to 480K (in six steps) were asked, where the control rods C, R1, and R2 have slightly different settings due to temperature elevation (13 mm).
The effective multiplication factors should be calculated for the following temperatures: 280, 300, 340, 380, 420, 460 and 480 Kelvin and the isothermal temperature coefficients should be calculated at: 290, 320, 360, 400, 440 and 470 Kelvin. The insertion depth of C, R1, R2 is the same at level =1776 mm and R3 again is fully withdrawn. Also the critical position for those control rods at 480K, with R3 fully out, is requested for the benchmark.

The following relation should evaluate the isothermal temperature coefficients for a fully loaded core from the effective multiplication factors:

$$r_n = \frac{k_{n+1} - k_n}{k_{n+1}.k_n} \cdot \frac{1}{(T_{n+1} - T_n)}$$

r_n : Temperature coefficient between T_n and T_{n+1} (Δk/k/K)

T_n : Core temperature at n^{th} measurement (K)
T_{n+1} : Core temperature at $n+1^{th}$ measurement (K)
k_n : Effective multiplication factor at T_n
k_{n+1} : Effective multiplication factor at T_{n+1}.

Results of the calculations are shown in Fig. 2. The calculated isothermal temperature coefficient (average between 320 K and 440 K) is –14.7 (pcm/^{o}C), while the measured value equals –14.2

(pcm/^{o}C) on the average. The calculated critical control rod position at 480 K is 1879 mm, while for the measurements at T= 395 K; 1873 mm and at T= 418 K; 1903 mm are found.

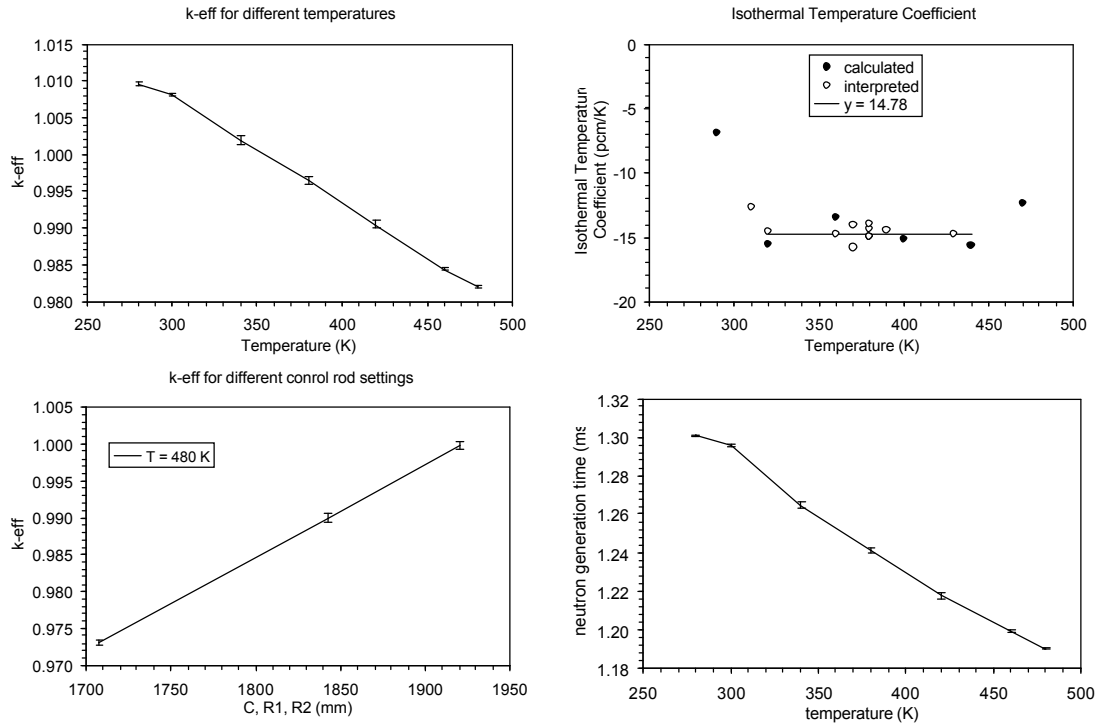

Figure 2: The effective multiplication factor (upper left) and isothermal temperature coefficient at different core temperatures, the multiplication factor for the different control rod settings of C, R1, R2 while R3 fully out (lower left) and the neutron generation time versus core temperatures (lower right).

4. The Reactivity and the Reactor Noise Measurements of the HTTR during the Start-up Cores

During the start-up phase of the HTTR at different core configurations, reactivity and the reactor noise measurements were carried out in parallel with measurements of the HTTR Physics group. For these measurements two temporary compensated ionisation chambers CIC-A and B were used. Fig.3 shows the horizontal cross-section of the core and the positions of the detectors. Measurements were carried out by using the signal processing system DSA-2 (Türkcan, 1993) in real-time. During the on-line reactivity experiments, the measured DC signals were digitised and the reactivity is calculated by using the Inverse Kinetics Method (IK).

During the first critical approach after the loading of the 19 th fuel assembly, the source criticality at very low power is achieved. For criticality, first the neutron source is removed and then by moving the central control rod (C) to compensate for the reactivity until the first criticality of the reactor is reached on Nov. 10 1998. Fig. 4 shows the result of reactivity measurements during this approach to criticality.

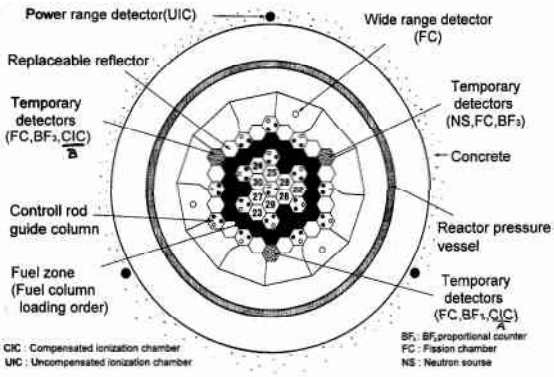

Figure 3. HTTR Horizontal positions of neutron detectors.

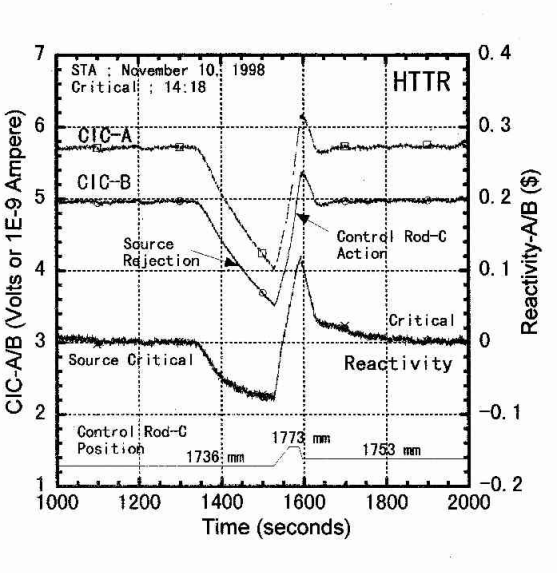

Figure 4. Approach to criticality.

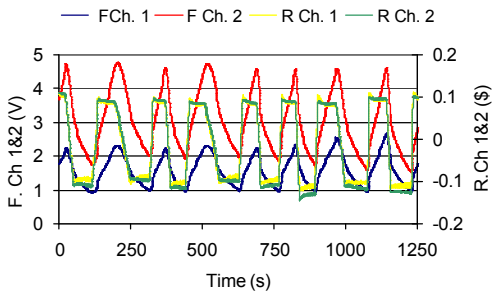

Figure 5. Measured reactivity at HTTR full core. Two measured signals of Ch1 (A) and Ch2 (B) and the computed reactivity (blocks match each other, scale on right).

After each new few fuel loading, the reactivity value of the control rods were measured successively with the IK-method by the HTTR physics group and by DSA-2 system. As an illustration the experimental result is given in Fig. 5 for full core with 30 fuel assemblies. By the move of a control rod with a small step, the neutron flux is increased while the reactor power is kept in the same power range by compensating the reactivity effect by another control rod. For each action where the reactivity is constant over about 80 seconds the calculated reactivity is averaged. This way the average reactivity worth of the control rod is determined for this stepwise change.

For the reactor noise measurements, the same neutron detector signals were used and the reactor at very low power is kept as stable as possible especially for this measurement. Signals were conditioned for the noise measurements by using high- and low-pass filters with a gain amplifier. Inherent to this type of reactors the neutron generation time is long which was calculated to be: 1.173±0.001 ms. The prompt neutron decay constant is quite close to the decay of the fastest delayed neutrons, therefore no intermediate plateau can be recognised in the measured spectral functions such as the Normalised Auto and Cross Power Spectral Density (NAPSD and CPSD). In Fig.6 an example is given from the measurements on the 21 fuel elements critical core at very low power. Our investigations indicated a shortcoming of the bandwidth of the used current amplifiers

due to the large cable capacity of about 100-m of cable between the detectors and the amplifiers. This situation was not possible to change during the measurements.
The measured coherence between the two neutron detector signals was 0.8 at 0.1 Hz and gradually decreased to 0.2 at 1 Hz and the phase between them practically zero. The calculation of the zero-power transfer function given in Fig.7 for different number of fuel loading, the transfer function shape did not changed considerable.

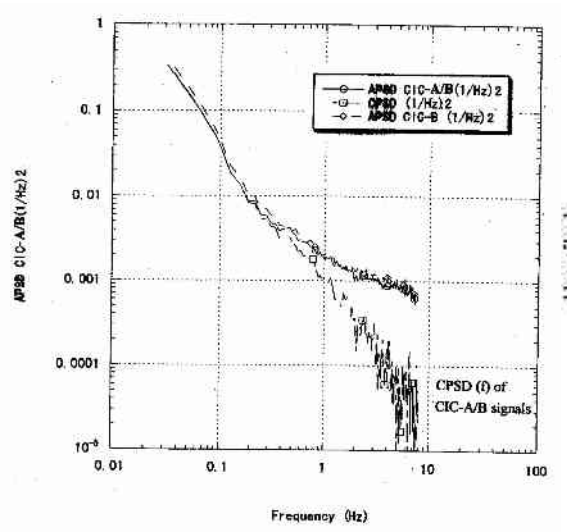

Figure 6: The NAPSD(f) and the NCPSD(f) functions measured 21st fuel loading. The cross spectra do not give clear break frequency.

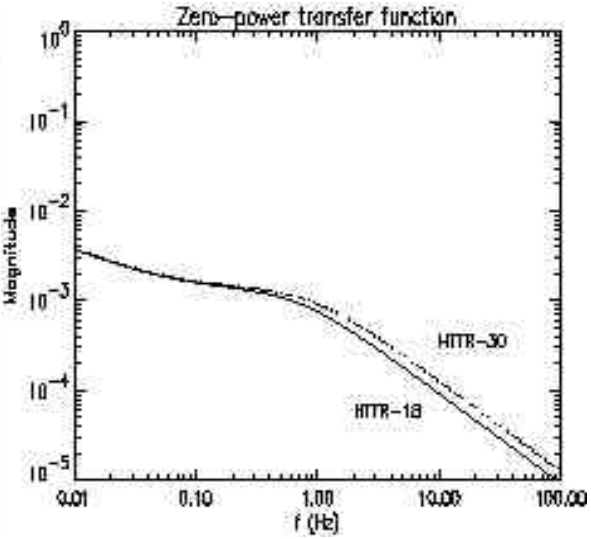

Figure 7: Calculated Transfer functions for 18 and 30 fuel elements loading.

5. Conclusions

On the level of cell calculations a good agreement has been obtained between the cross sections and the spectra as prepared by the SCALE-system and as prepared by WIMS. Calculations with detailed geometry converged to very good agreement between the results of PANTER and the results of KENO with an exact geometrical model. In the second phase, KENO results gave very well the measured values of the scram reactivities as well as the estimation of the isothermal temperature coefficient within the requested temperature interval. Therefore, we can conclude that the Benchmark calculations of the start-up physics calculations were successful and that the results of the reactivity measurements and the reactor noise analysis done at the HTTR, using the DSA-2 system, resulted with a good agreement with the results of the HTTR Physics Group.

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