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Calculational Results for the Benchmark Problems of the HTR-10 Initial Core

Author(s)

U. Ohlig

Organisation, Country

FZJ Research Centre Jülich
Institute for Safety Research and Reactor Technology (ISR)
D-52425 Jülich, Federal Republic of Germany

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1. Introduction

Within the frame of the HTR-N project in the 5th European Research Programme the critical loading, the control rod worth, and the isothermal temperature coefficients at zero power conditions of the Chinese 10MW$_{th}$ High-Temperature Reactor (HTR-10) have been determined with the reactor code system VSOP employed at the Institute of Safety Research and Reactor Technology(ISR) of the Research Centre Jülich. This code system is used as the main tool for design studies of high temperature reactors, and therefore, the validation of this code, specifically the accuracy in control and shutdown margins calculations, are of particular interest.

2. Definition of the Benchmark Problems

A system of benchmark problems has been defined by the Institute of Nuclear Energy Technology (INET) /1/. It consists of three parts:

- **benchmark problem B1**: prediction of the initial critical loading height under helium atmosphere and at a core temperature of 20^{0}C with all control rods at their withdrawn position,
- **benchmark problem B2**: calculation of the effective multiplication factor of the full core (5m^3) under helium atmosphere and with the control rods at their withdrawn position at three different core temperatures:
    - 20^{0}C (problem B21),
    - 120^{0}C (problem B22),
    - 250^{0}C (problem B23),
- **benchmark problems B3 and B4**: **for the full core**, calculation of the reactivity worth of the ten fully inserted control rods (B31), and of one fully inserted control rod (B32, the other rods should be at their withdrawn position), **for a core loading height of 126 cm**, calculation of the reactivity worth of the ten fully inserted control rods (B41) and the determination of the differential reactivity worth of one control rod (B42, the other rods are at the withdrawn position). The differential reactivity worth should be calculated at the following axial positions of the lower end of the rod: 394.2cm, 383.6cm, 334.9cm, 331.3cm, 282.6cm, 279.0cm, 230.3cm. For these benchmark problems the core conditions are: helium atmosphere and 20^{0}C.

These benchmark problems have been proposed for the initial core and for a simplified core physics model described in /1/ and which has been provided as a common starting point for the different calculational models of the European partners. For the initial core loading, the HTR-10 has been filled with a mixture of fuel and graphite pebbles (mixing ratio 57:43%). The cone region and the discharge tube at the core bottom are loaded with graphite (dummy) balls, only.
The full core volume of 5m^3 means the total volume of all mixed balls and of the graphite balls in the cone region, the loading height is defined as the height of the mixed balls starting from the upper surface of the cone region.
The core temperature is defined as the temperature of the balls and of all the surrounding structures, included in the simplified core model as presented in Fig.2.
The control rods are "fully withdrawn" when their lower end is at the axial position of 119.2cm, and their insertion depth at their "fully inserted" position is 394.2cm.

3. Calculational Methods and Nuclear Data

The benchmark problems are calculated using the following parts of the VSOP /2/ code system: the ZUT /3/, GAM-1 /4/, THERMOS /5/, and the CITATION /6/ code. The code system considers the following main features of pebble bed reactors:

- the double heterogeneous nature of the spherical fuel elements with the coated particles,
- the streaming correction of the diffusion constant in the pebble bed,
- detailed leakage feedback when using few group homogenised cross sections in the whole core diffusion calculation,
- the use of anisotropic diffusion constants in the upper cavity and in the channels of the control rods and of the small absorber balls.

Self-shielded cross sections in the resolved resonance region of U^{238} are generated by the ZUT code taking into account the double heterogeneity of the fuel elements. The resonance parameters processed by the ZUT code are taken from the JEF-1 data file /7/.
Spectrum calculations are performed by a combination of the epithermal spectral code GAM-1 and the thermal cell code THERMOS using two fine group nuclear data libraries /8/ based on JEF-1 and ENDF/B-V: an epithermal library with a 68 energy group structure ranging from 10 MeV to 0.414 eV, and a thermal library with 30 fine energy groups in the energy range from 2.05 eV to 10^{-5} eV.
The 0-d spectrum code GAM-1 applies the P_1–approximation to homogenised spectrum zones. Neutron leakage between adjacent spectrum zones is considered by buckling terms determined from the fast and epithermal leakage values of the whole core diffusion calculation and transferred to the spectrum calculation. At the beginning all buckling terms are zero. Condensation of the fine energy groups is performed to three broad groups used in the diffusion calculation.
The thermal cell code THERMOS performs 1-d transport spectrum calculations using a heterogeneous cell model. The grain structure of the coated particles inside the fuel elements is taken into account. The neutron exchange between neighbouring spectrum zones is considered in the form of albedo terms at the cell surface. They are calculated from the thermal leakage value of the diffusion calculation and booked into the fine thermal energy groups. At the beginning of the leakage iteration a white boundary condition is assumed at the outer surface of the cell. A cell-weighted condensation of the 30 fine group cross sections is performed to one broad energy group used in the diffusion calculation.
The broad group structure in the energy range from 10 MeV down to 10^{-5} eV is shown in Table 1.

Group	Upper Energy Boundaries (eV)
1	$1.0 \cdot 10^{7}$
2	$1.111 \cdot 10^{5}$
3	29.0
4	1.86

Table 1: Group Structure in the VSOP Diffusion Calculations

The eigenvalues and flux distributions of the whole reactor are calculated by the diffusion code CITATION in 2-d r,z and 3-d r,φ,z geometry.
A streaming correction of the diffusion constants in the pebble bed is calculated according to Lieberoth /9/. In the upper void region the method of Gerwin and Scherer /10/ is applied. For the

boring holes of the control rods and of the small absorber balls a special transport calculation was performed in order to determine the corresponding diffusion constants.
The geometric dimensions of the fuel elements and core components and the atom number densities of the materials given in Ref. 1 are used.

4. Unit Cell Models

According to the initial core loading of the HTR-10 - the inner cone region at the bottom of the core is filled with graphite balls, then, a mixture of fuel and graphite balls in the ratio of 0.57 to 0.43 is loaded gradually to approach first criticality- two kinds of spherical unit cell models are chosen: a fuel and a dummy (graphite) unit cell model.

1. The fuel unit cell model shown in Fig.1 consists of 4 zones: a fuel zone, containing the coated particles (cp) and the graphite matrix, the graphite shell, a helium or air gap as third zone corresponding to the packing fraction of 0.61, and a graphite/ helium or air mixed zone as mock-up for the moderator pebbles and their corresponding void space. The coated particles grain structure inside the fuel zone is treated by effective macroscopic total cross sections replacing the homogenised macroscopic cross sections of the matrix and the coated particles.
2. The dummy unit cell model consists of two zones: a graphite zone with r= 3 cm, and a void corresponding to the filling fraction f= 0.61 of the dummy balls in the cone region.

The k_∞-value of the fuel cell calculation is: 1.7475 at T= 293 K using a white boundary condition.

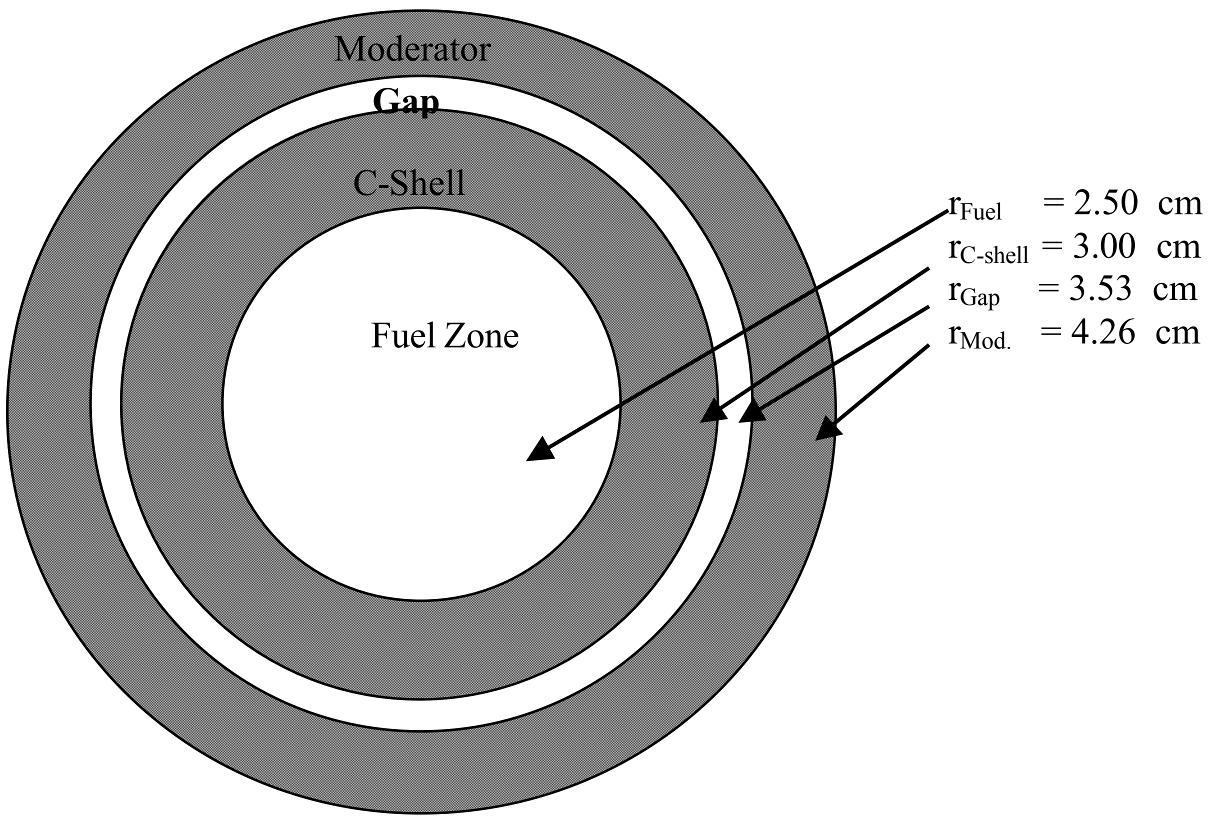

Fig. 1: 1-d Spherical Fuel Cell Model for THERMOS

5. Whole Reactor Calculations

Using the 4-group constants from the GAM-1 and THERMOS cell calculations the whole HTR-10 reactor is modelled with the CITATION diffusion code.Two geometric models are chosen in order to compare the results: a 2-d r,z model as presented in Fig. 2 and a 3-d r,φ,z model. The assembly is modelled by dividing the volume into different spectrum zones each comprising several material compositions given in Table 2 of Ref. 1. There are 16 different spectrum zones. The active core

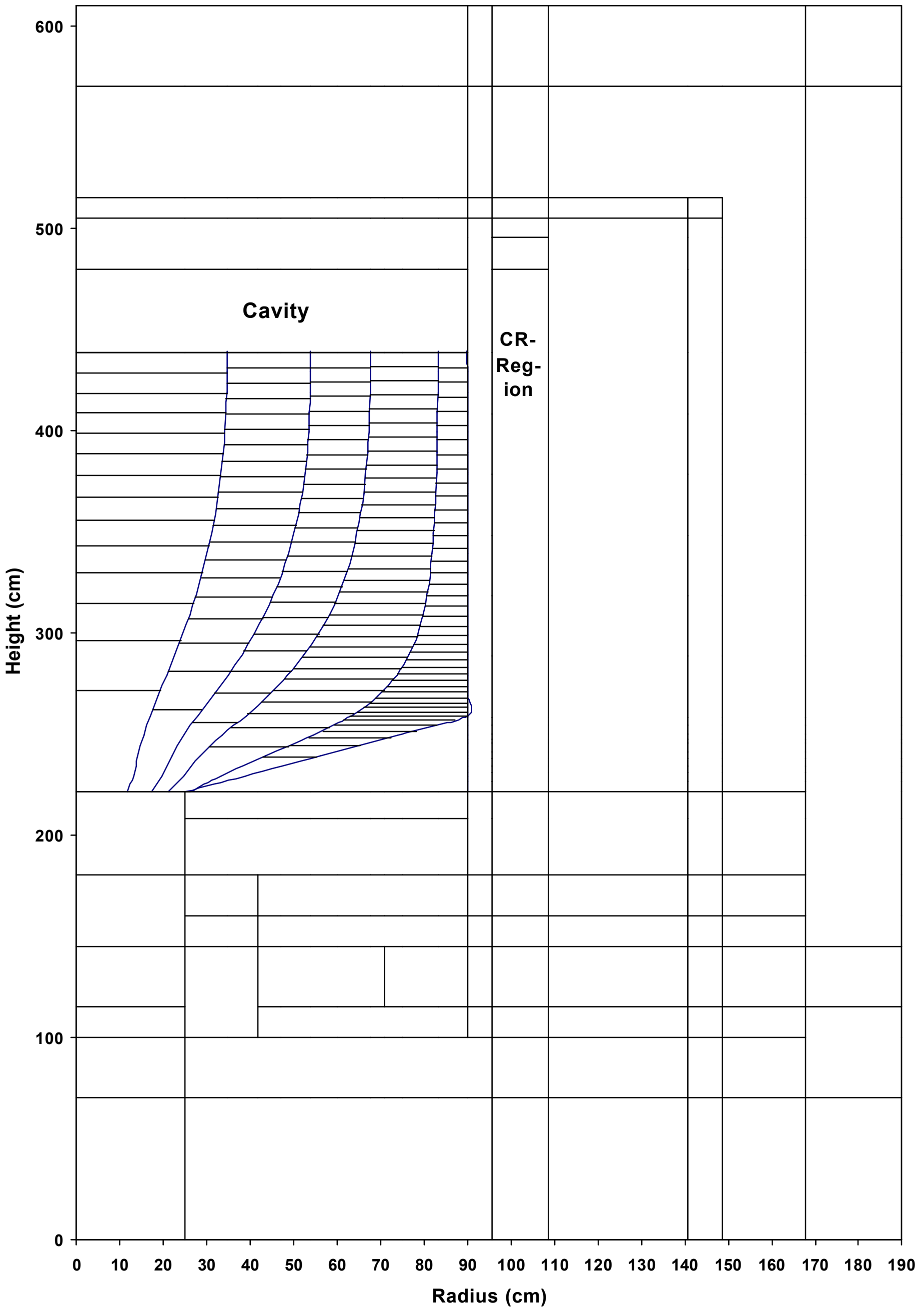

Fig. 2: 2-d Core Physics Calculational Model of the HTR-10, used for VSOP

and the adjacent reflector regions are subdivided into smaller spectrum zones in order to take into account the core/reflector coupling accurately during the leakage iteration. In the geometric model shown in Fig.2 the core is divided into five channels in order to consider the flow of the pebbles with different speeds during the fuel shuffling. Each channel is subdivided into axial regions, for each region a set of macroscopic cross sections will be generated. In the case of the HTR-10 initial core, no shuffling had to be considered.

In the 3-d calculations the boring holes of the ten control rods and the seven channels for the small absorber balls are explicitly taken into account using anisotropic streaming coefficients in the remaining voids. All other channels or holes, as e.g. the helium flow channels, the hot gas duct, the three irradiation channels, are neglected. The control rods in the reflector in their withdrawn position (the lower end of the control rods is at the axial position of 119.2 cm) are also considered in the 3-d geometry.

6. Control Rod Worth Calculations

As the diffusion method is generally not valid inside or in the vicinity of strong absorber regions, combined transport-diffusion methods have been developed in order to handle this problem. The basic idea is to model the absorber and its environment by transport theory, in order to extract some macroscopic data from the transport solution and to use these data in a subsequent 3-d diffusion calculation for the whole core. One of these methods, the "Method of Equivalent Cross Sections", has been developed at the ISR /11/. When using this method, both the absorption in and the leakage into the absorber region are the same in diffusion and in the more accurate transport calculation. For this purpose the following steps have to be achieved:

- 1-d unit cell transport calculation for the heterogeneous absorber region using the 1-d integral spectrum code TOTMOS /12/. The cylindrical cell model for the control rod region is presented in Fig. 3. It has to be pointed out that the mesh size in the absorber region and its immediate neighbours is prescribed by the mesh grid in the diffusion calculation.
- Calculation of the equivalent few group macroscopic cross sections and the equivalent diffusion constants by the code RODCIT /13/.
- 3-d whole core calculation using diffusion theory and the equivalent macroscopic cross section data in the control rod region.

This method of equivalent cross sections is also applied here to the HTR-10 control rods and the equivalent diffusion parameters obtained are used to evaluate the reactivity worth for the whole core.

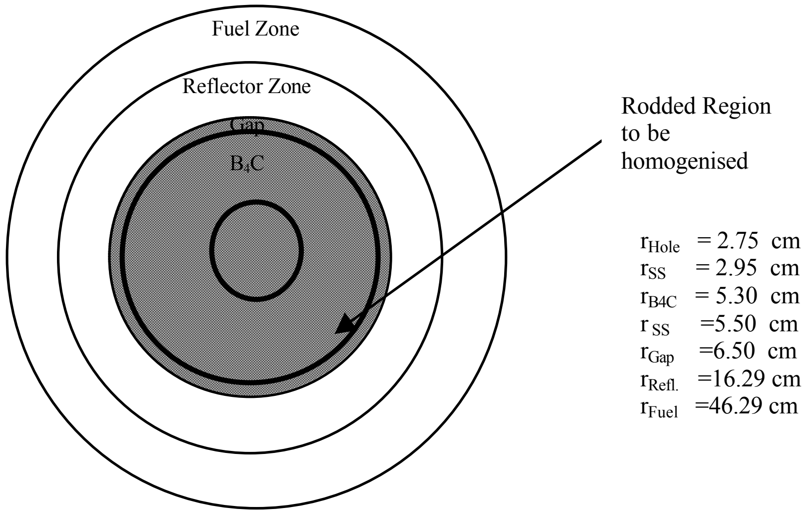

Fig. 3: 1-d Cylindrical Model of the CR-Cell for TOTMOS

7. Calculational Results

7.1 Benchmark Problem B1 (Initial Criticality)

As mentioned above, two series of diffusion calculations are performed for each of the different core loading heights, needed to determine the critical core height:

- one in 2-d geometry considering the empty CR- and KLAK-channels by homogenised atom densities as given in Ref. 1,
- and a second one in 3-d geometry taking into account the neutron streaming in the channels of the CR's and KLAK's and the CR insertion into the side reflector until an axial position of 119.2 cm.

The results of both series, presented in Table 2 and Fig. 4, differ considerably. The consideration of the large holes with their increased neutron streaming causes a difference in k_{eff} of about $\Delta k \approx 0.01$. Consequently, the corresponding critical core heights differ about 2.6 cm: when considering the CR-channels by homogenised atom densities in the 2-d diffusion calculation the critical loading height is: **H_{crit} = 124.2 cm**, corresponding to 9716 fuel and 7330 dummy balls, but when considering the CR- and KLAK-boring holes explicitly in the 3-d diffusion calculation the critical height amounts to**: H_{crit} = 126.8 cm**, corresponding to 9912 fuel and 7477 dummy balls. The latter result is in excellent agreement with the MCNP Monte Carlo result of the INET/14/.

H_{core} (cm)	k_{eff}-Values at T= 20^0 C		
	2-d geometry	Δk	3-d geometry
180.12	1.13725	0.0106	1.12665
170.12	1.11870		
160.11	1.09836		
150.10	1.07545	0.0106	1.06483
140.09	1.04919		
130.09	1.01961	0.0087	1.01087
126	1.00639	0.0088	0.99736
120.08	0.98601	0.0089	0.97714
H_{crit} (cm)	**124.2**		**126.8**

Table 2: Results of the Diffusion Calculations for the Original Benchmark Problem B1

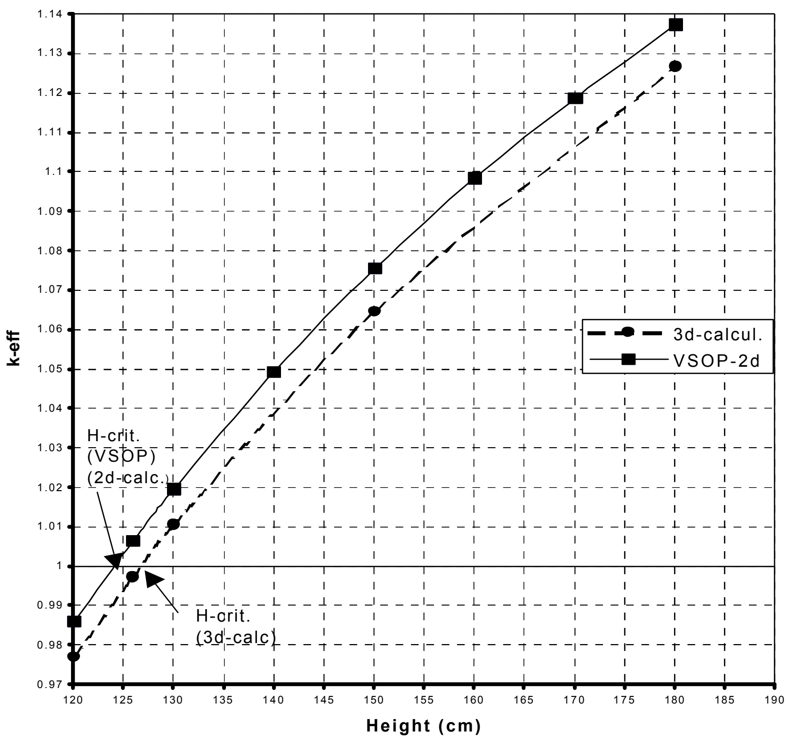

Fig.4: k_{eff} versus Core Height of the HTR-10 (Original Benchmark Problem B1)

7.2 Benchmark Problem B2 (Temperature Coefficients)

The temperature dependence of the k_{eff} –values is also determined with and without taking into account the boring holes of the CR's and KLAK's. The results are presented in Table 3. In both series, the difference between multiplication constants at different core temperatures remains constant, but the difference itself is considerably high compared to the INET/14/ results. The reason for this discrepancy could not yet be identified and further calculations will be made in order to clarify this point.

Problem	B21	B22	B23
T (^{0} C)	20	120	250
k_{eff} 2-d geometry 3-d geometry	 1.13725 1.12665	 1.12404 1.11331	 1.10693 1.09588
Δk 2-d geometry 3-d geometry	 -0.0132 -0.0133	 -0.0171 -0.0174	

Table 3: Results of the Diffusion Calculations for the Original Benchmark Problem B2

7.3 Benchmark Problems B3 and B4 (Control Rod Worth)

The calculational results of the control rod worth are obtained by whole core diffusion calculations using the method of equivalent cross sections as described above. To determine the reactivity change associated with the insertion of ten or one control rods, respectively, the CITATION calculations are performed in 3-d geometry on the one hand for the unrodded core (all ten control rods are withdrawn , that means: the lower end is at z= 119.2 cm-4.5cm =114.7cm) and on the other hand for the rodded core (ten /one control rods are/is fully inserted with the lower end at the axial position of z= 394.2cm-4.5cm= 389.7cm). The lower and upper end cups of the control rods are not considered in the calculations. The neutron streaming effect in the void areas of the control rod channels is taken into account by anisotropic diffusion constants where D_z and D_r are obtained by comparing results of transport and diffusion solutions concerning identical void spaces and adjusting the diffusion constants by the results of the transport calculation.
All results for the control rods at fully loaded core (benchmark problem B3) and at a core height of 126 cm (benchmark problem B4) are summarised in Tables 4, 5 and 6. The differential reactivity worth of one control rod at 126 cm core height (benchmark problem B42) is given in Table 7 and Fig. 5. As can be noticed, the bank worth of the ten control rods agrees quite well with the result obtained by the Monte Carlo calculations of the INET /14/. It demonstrates that the difference between the two reactivity states is well reproduced by the CITATION calculation and the method of equivalent cross sections. In the case of one control rod, the reactivity worth calculated by this method is overestimated by about 10%, compared to the Monte Carlo result /14/. An explanation for this discrepancy could be that the boundary condition used in the rod cell model describes the situation better for the ten control rods than for one single rod. But, when considering the standard deviation given for the Monte Carlo calculations of the INET/14/, the reactivity worths of one

single rod (benchmark problems B32 and B42) lay inbetween the statistical uncertainty (2σ): $\Delta\rho = \pm 0.265$ % (B32) and $\Delta\rho = \pm 0.371$% (B42). The distribution of the thermal neutron flux in the HTR-10 core with one fully inserted control rod is shown in Fig.6.

All results of the original benchmark problems are summarised in Tablle 8.

Loading Height of the Core (cm)	Nr. of Fully Inserted Control Rods	k_{eff} 10 Control Rods withdrawn	k_{eff} Fully Inserted Control Rods	Worth ($\Delta k/k$%)
180	10	1.1266	0.9490	16.60
	1		1.1071	1.56
126	10	0.9974	0.8277	20.5
	1		0.9782	1.97

Table 4: Reactivity Worth of One and of Ten Control Rod(s) at Different Core Heights together with the Corresponding k_{eff}-Values (Original Benchmark Problems B3 and B4)

Problem	B31 ρ[%$\Delta k/k$] 10 rods inserted, 20^0 C	B32 ρ[%$\Delta k/k$] 1 rod inserted, 20^0 C
VSOP-CITATION 3d-calculation	16.60 %	1.563 %
MCNP (INET)	16.56%±0.31%	1.413%±0.265%

Table 5: Reactivity Worth of the Control Rods at Full Core (Original Benchmark Problem B3)

Problem	B41 ρ[%$\Delta k/k$] 10 rods inserted, 20^0 C	Integral Rod Worth ρ[%$\Delta k/k$] 1 rod inserted, 20^0 C
VSOP-CITATION 3d-calculation	20.55 %	1.969 %
MCNP (INET)	19.36%±0.44%	1.793%±0.371%

Table 6: Reactivity Worth of the Control Rods at 126 cm Core Height
(Original Benchmark Problem B4)

Axial Position (cm)	Rod Worth $\rho[\%\Delta k/k]$
230.32	0.4207
279.02	0.9424
282.62	0.9976
331.32	1.679
334.92	1.716
383.62	1.968
394.20	1.969

Table 7: Differential Worth of One Control Rod at 126 cm Core Height
(Original Benchmark Problem B42)

Benchmark Problem		Original Benchmark	
		VSOP in 2-d r,z Geometry	VSOP in 3-d r,φ,z Geometry
B1		124.2 cm	126.8 cm
B2	B21	1.1373	1.1266
	B22	1.1240	1.1133
	B23	1.1069	1.0959
B3	B31		16.60%
	B32		1.56%
B4	B41		20.55%
	B42		1.97%

Table 8: All Calculational Results for the Original Benchmark Problems of the HTR-10 Initial Core

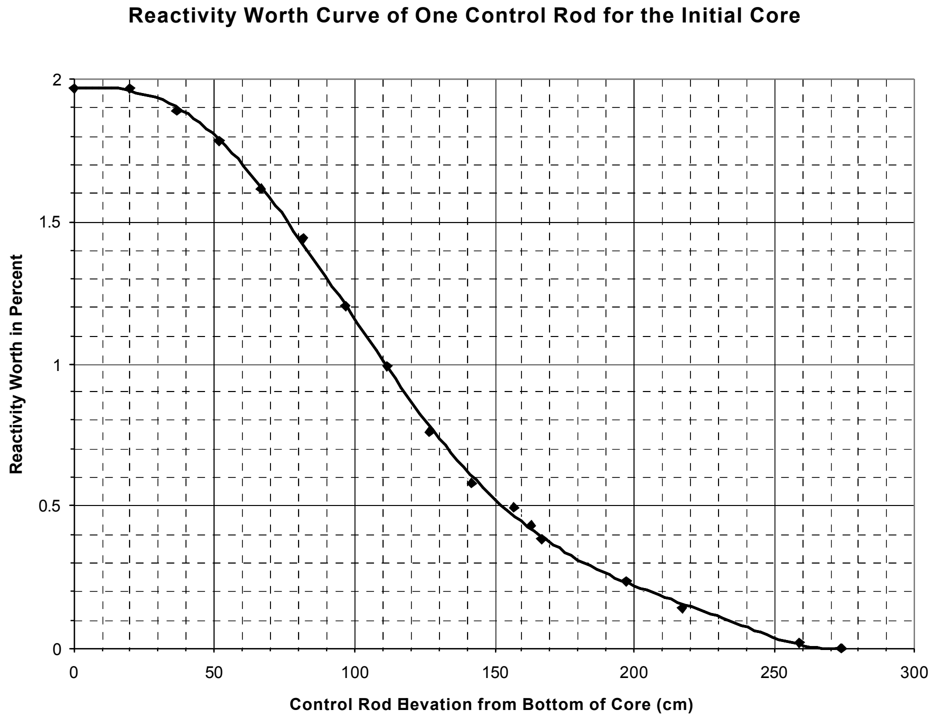

Fig.5: Reactivity Worth Curve of One Control Rod (S1) for the HTR-10 Initial Core (Original Benchmark Problem B42)

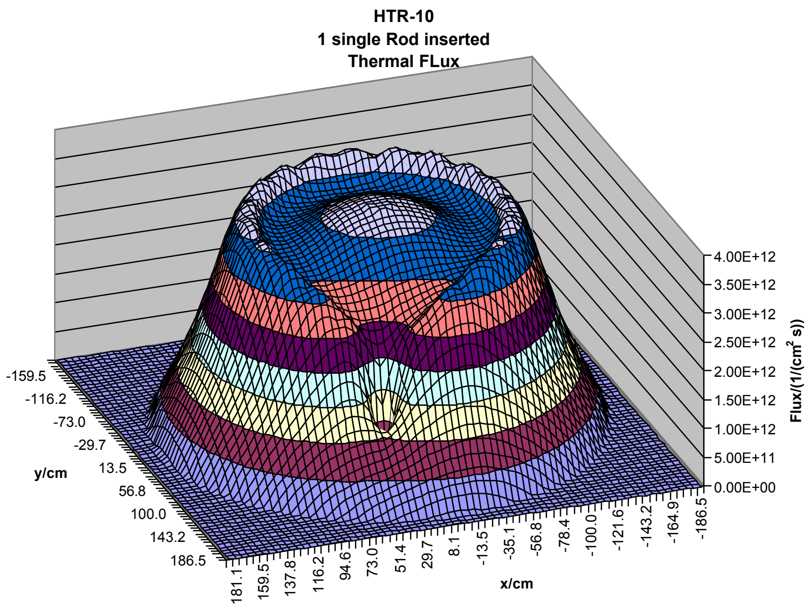

Fig.6: HTR-10 Thermal Neutron Flux with One Control Rod Fully Inserted

8. Calculational Results for the Deviated Benchmark Problems

It turns out that the HTR-10 got critical with 16890 pebbles in the core, 9627 fuel pebbles and 7263 moderator pebbles, under air condition and being loaded with another kind of moderator pebbles than defined in the original benchmark description. The core temperature was 15^0 C and the critical core height was: **$H_{crit.}$ =123.06 cm**. Compared to the description of the original benchmark problems three conditions have been changed:

- Density of dummy balls: 1.73→1.84 g/ cm^3
- B_{imp} in dummy balls: 1.3→0.125 ppm
- Core atmosphere at initial criticality: helium→humid air

When considering these revised data in the unit cell calculations and in the whole core diffusion calculations the first criticality is determined to:

- in the case of the 2-d diffusion calculations: **$H_{crit.}$= 121.0 cm**,
- in the case of the 3-d diffusion calculations: **$H_{crit.}$= 123.3 cm.**

The latter result is in excellent agreement with the experiment. All results for the deviated benchmark problems are summarised in Table 9. The differential reactivity worth of one control rod at a core loading height of 126 cm is given in Table 10. Similar tendencies as observed in the results for the original benchmark problems, e.g. strong temperature dependence of the multiplication constants, a quite good agreement with the Monte Carlo results of the INET concerning the bank worth of the ten control rods, and a relatively high reactivity worth of one control rod, can be noticed also in the results for the deviated benchmark problems.

Benchmark Problem		Deviated Benchmark	
		VSOP in 2-d r,z Geometry	VSOP in 3-d r,φ,z Geometry
B1		121.0 cm	123.3 cm
B2	B21	1.1468	1.1368
	B22	1.1334	1.1232
	B23	1.1160	1.1054
B3	B31		15.73%
	B32		1.48%
B4	B41		19.31%
	B42		1.86%

Table 9: All Calculational Results for the Deviated Benchmark Problems of the HTR-10 Initial Core

Axial Position (cm)	230.32	279.02	282.62	331.32	334.92	383.62	394.20
Rod Worth ρ[%Δk/k]	0.4355	0.9703	1.017	1.736	1.762	1.852	1.865

Table 10: Differential Worth of One Control Rod at 126 cm Core Height
(Deviated Benchmark Problem B42)

9. Conclusion

The calculational results of the original and the deviated benchmark problems are summarised in Tables 8 and 9, respectively. 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. It has to be pointed out that there is an excellent agreement between the 3-d diffusion calculation and the experiment concerning the critical core height. Furthermore, the strong temperature dependence of the effective multiplication constant is remarkable, and this effect has to be investigated in further calculations. Moreover, it turns out that the bank worth of the ten control rods is in good agreement with Monte Carlo results, whereas the reactivity worth of one control rod overestimates the corresponding value obtained by the Monte Carlo code MCNP, but lays inbetween the statistical uncertainty (2σ).

10. Acknowledgement

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