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HTR-10: Design and Calculation of the Equilibrium State

Claudia Druska (FZJ), Stephan Struth (FZJ)

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Summary

This document contains a description of the equilibrium core of the HTR-10 and the current state.

Approval

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0	First issue	S. Struth (FZJ) 21/06/2012	M. Buck (IKE)	N. Kohtz (TUV) 31/10/12	S. de Groot (NRG) 31/10/12

Distribution list

Name	Organisation	Comments
P. Manolatos	EC DG RTD	
All technical participants	ARCHER	
Steering Committee members	ARCHER	

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1 Design of the HTR-10

1.1 Background

In the framework of an IAEA benchmark [1] in 2003 calculations with VSOP(99/05) were performed in Jülich to investigate the initial criticality in the HTR-10. The minimal filling level in the atmosphere of air that is needed for the first criticality should be calculated.

So only the filling of the core with balls (fuel and dummy elements) and the grid for the neutron flux had to be modelled.

The calculations of temperature fields and gas flow were not provided and the fuel shuffling was not performed either.

Figure 1 shows the "CITATION" grid for the calculation of the neutron flux, as it was defined in the benchmark conditions.

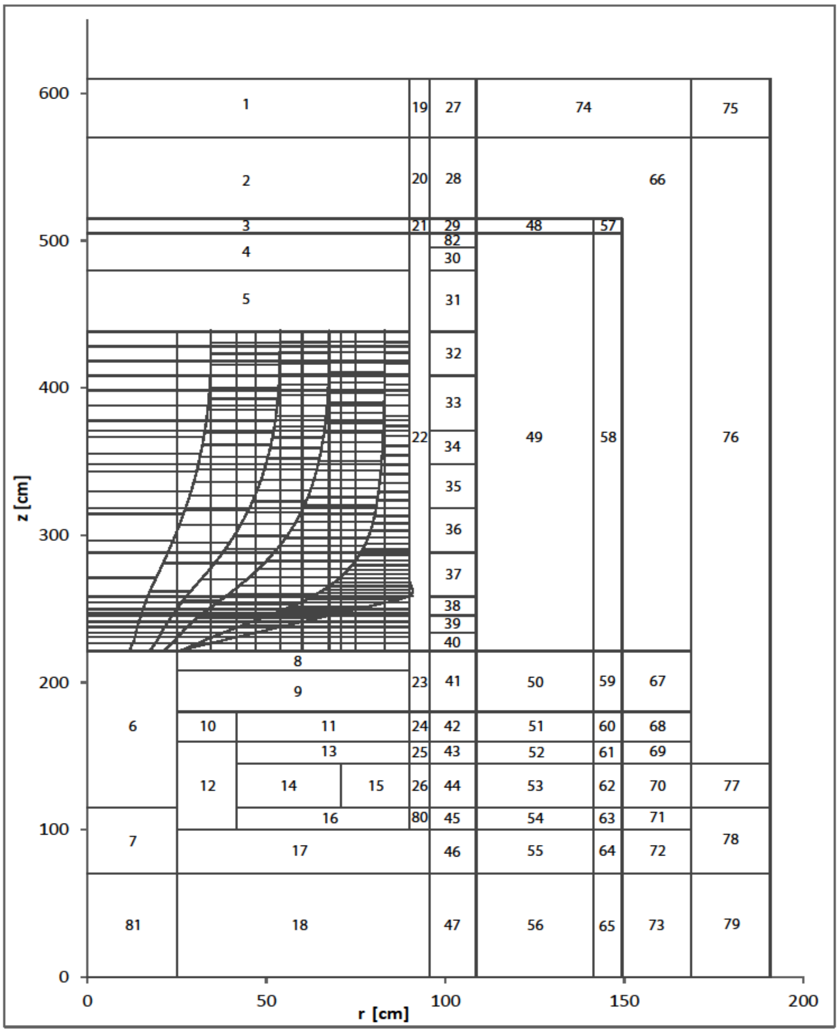

Figure 1: HTR-10 CITATION grid.

This grid is based on a flow channel model in the area of the reactor core as shown in Figure 2. The cylindrical core with conical bottom is divided into 5 floating channels whereof each channel is subdivided into a number of equal-sized regions (see Table 1).

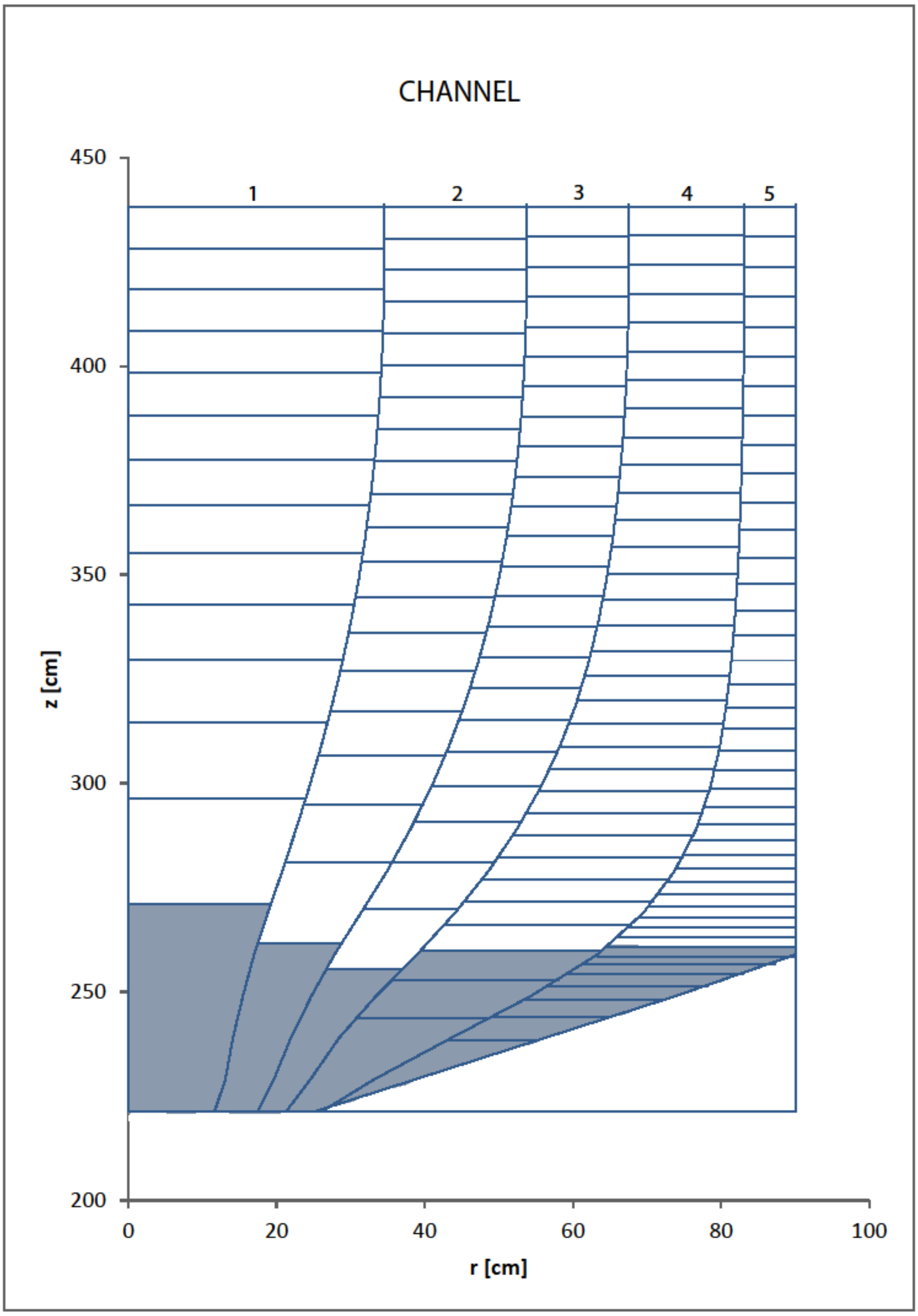

Figure 2: Flow channel model with regions.

The course of the flow lines, i.e. the boundary of each channel was taken from [2].

In order to calculate the benchmark each region was provided according to the specifications into two batches, the larger one (57 vol-%) filled with spherical fuel elements, the smaller one (43 vol-%) filled with dummy elements. The cone is filled with 100 vol-% dummies.

To realise a relatively flat surface of the cone area the number of regions per channel has been doubled compared to the specifications (see Figure 2, especially the gray-colored cone-regions).

Table 1: Channels, Regions, Volumes.

Channel	Region	Region volume	Percentage of the total volume	Original volume of a batch
1	14	37134 cm^3	0.19189	7426.8 cm^3
2	20	40480 cm^3	0.20918	8096.0 cm^3
3	24	37688 cm^3	0.19475	7537.6 cm^3
4	32	51263 cm^3	0.26490	10252.6 cm^3
5	42	26953 cm^3	0.13928	5390.6 cm^3

1.2 Modeling of the equilibrium core

For the calculation of the reactor in the equilibrium state the consideration of the pebble flow is required. Therefore the subdivision of the channels into equal volumes per channel is necessary.

Depending on the location the fuel elements move with different speed through the core. For this reason, the core is divided into 5 flow channels.

In each shuffling step a whole region for each channel is discharged. Therefore, the pebbles move faster in channels with fewer but larger regions, as in channels with many small regions. So, the fuel elements of the inner channel (14 regions) flow 3 times as fast as the fuel elements of the outer channel with 42 its regions.

The channels or regions are in contrast to the benchmark divided into 5 batches. This takes into account to the requirement that the reactor is operated as "5-fuel-passage-through-the-core". This means that a fuel element flows through the core five times before it is discharged. Therefore 5 different fuel states must be represented in each region. In the beginning of the calculation the 5 batches of a region have an equal volume.

During circulation, the dummy elements were successively discharged. After several cycles an equilibrium state will be reached. At this point of time each batch of a region is loaded with fuel elements with different burn-up. This difference depends on the number of passes through the core of the fuel element.

In addition to the modification of the fuel handling for calculating the temperatures and the gas flow two completely new mesh grids had to be developed including the necessary inputs for these mesh grids.

Based on the geometrical and thermal-hydraulic data from [1], [3], [4], [5] and [6] the grids for THERMIX (solid grid: heat conduction, heat radiation, solid temperature, power density; see Figure 3) and KONVEK (gas flow grid: flow of the cooling gas, heat transfer, gas temperature, gas pressure; see Figure 4) were created.

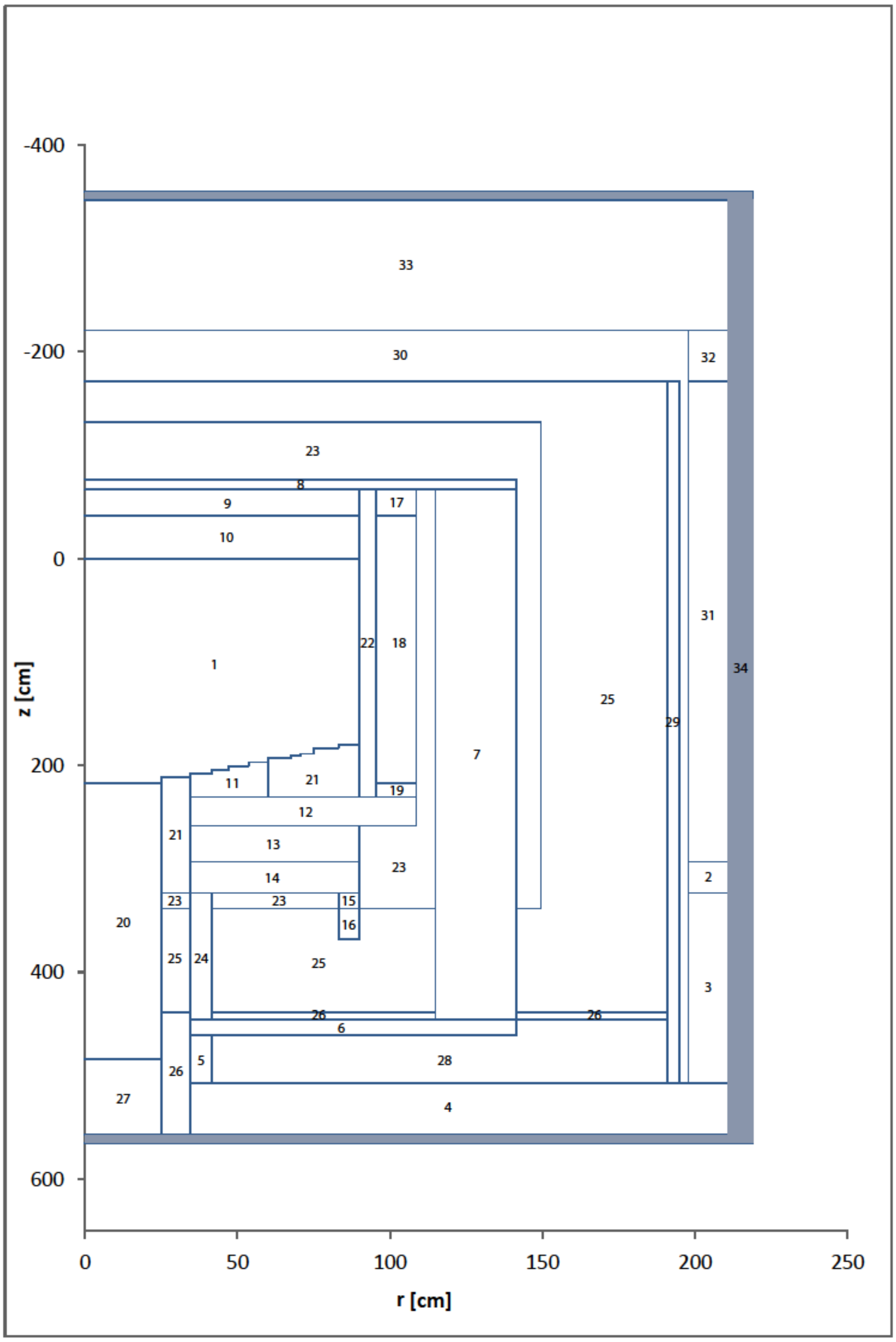

Figure 3: Solid grid (THERMIX).

Figure 3 shows the mesh grid of the solid part THERMIX with the allocation of areas (compositions) inside the reactor pressure vessel (34).
The air cavity outside the reactor pressure vessel (35), the steel wall at the side heat transport zone (36) and the heat transport zones with constant temperature (37-39) are not shown.

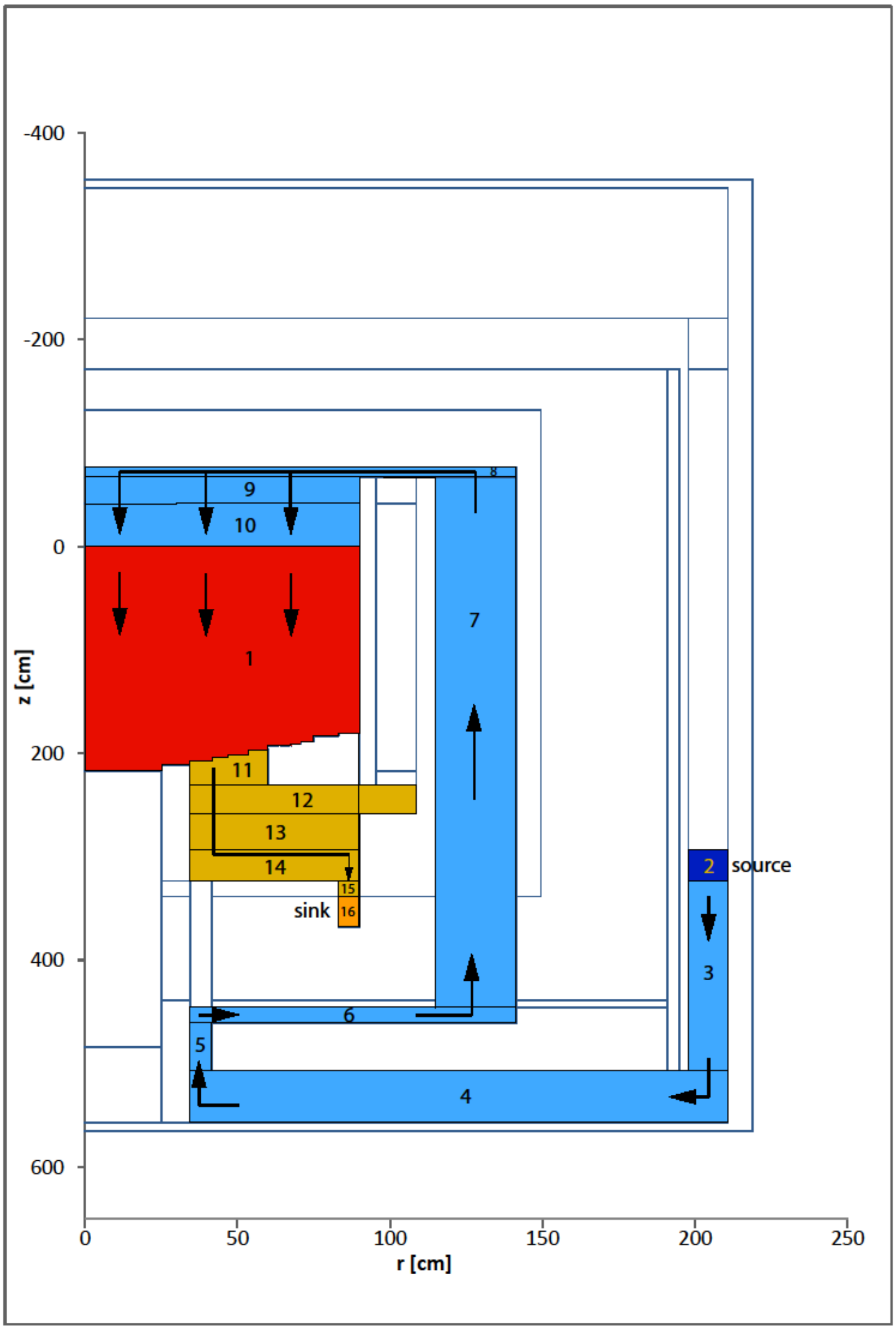

Figure 4: Convection grid (KONVEK).

The mesh grid follows the model of [6]. However, the composition numbers have chronological order and are compatible with the composition numbers of the fluid part KONVEK. With the exception of the reactor core (1), the first composition numbers were numbered; starting at the source of the coolant flow and up to the sink, see Table 2. After that, the compositions without coolant flow follow.

Table 2:Compositions in the solid model and the convection model.
Legend of Figures 3 and 4.

No.	Description solid model	No. in the convection model
1	reactor core	1
2	entry of the cooling gas at the inner surface of the RPV	2
3	flow path at the inner surface of the RPV	3
4	bottom cavity for cooling gas inside RPV	4
5	cooling gas flow path (cold)	5
6	cooling gas feeding to the side reflector (cold)	6
7	side reflector with cooling gas flow paths (cold)	7
8	cooling gas plenum in top reflector (cold)	8
9	top reflector with flow paths (cold)	9
10	gas plenum at core entry	10
11	upper bottom reflector with flow paths	11
12	gas plenum in bottom reflector (hot) with bypass	12
13	lower bottom reflector with flow paths	13
14	gas plenum at bottom reflector (hot)	14
15	feed pipe to the exit	15
16	cooling gas exit (hot)	16
17	side reflector with control rod channels	
18	side reflector with control rod channels	
19	side reflector with control rod channels	
20	upper fuel discharging tube	
21	bottom reflector without flow path	
22	side reflector without flow path	
23	top, side and bottom reflector without flow path	
24	steel structure	
25	carbon brick	
26	reactor bottom steel supporting structure	
27	lower fuel discharging tube	
28	reactor bottom steel supporting structure	
29	side helium gap inside core vessel	
30	core vessel	
31	side helium gap between core vessel and RPV	
32	steel structure	
33	upper helium cavity inside RPV	
34	reactor pressure vessel (RPV)	
35	air cavity outside RPV	
36	steel wall	
37	lower heat transport zone (constant temperature)	
38	side heat transport zone (constant temperature)	
39	upper heat transport zone (constant temperature)	

The area outside the reactor pressure vessel is in comparison with [6] regarded in radial direction only up to the cooling elements, in which a constant temperature of 50°*C* is given. The more external areas are not relevant to calculate the radial heat dissipation.

Figure 4 shows the grid of the fluid convection model with all areas (compositions) within the reactor pressure vessel. Here only the areas with fluid flow are numbered and highlighted. Again, the composition numbers are now arranged chronologically.

2 Results of the calculation of the equilibrium core

To determine the equilibrium core several iterative VSOP calculations were made until an appropriate value k_{eff} was achieved. Due to the predetermined very high enrichment of the fuel (17 wt.-%), a higher value (see Table 3) is arising relative to the predetermined expected value at the middle burn-up of the discharged fuel (80000 *MWd/t*).

Furthermore the period of time that is necessary to reach the equilibrium state is unexpectedly high. This is caused by the abnormal loading of the first core with a mixture of fuel pebbles and dummies.
This fact is discussed in detail in Chapter 3.

The Figures 5 and 6 show the multiplication factor k_{eff} and the burn-up values for each shuffling step. It can be seen in both figures that the values tend to an equilibrium state.

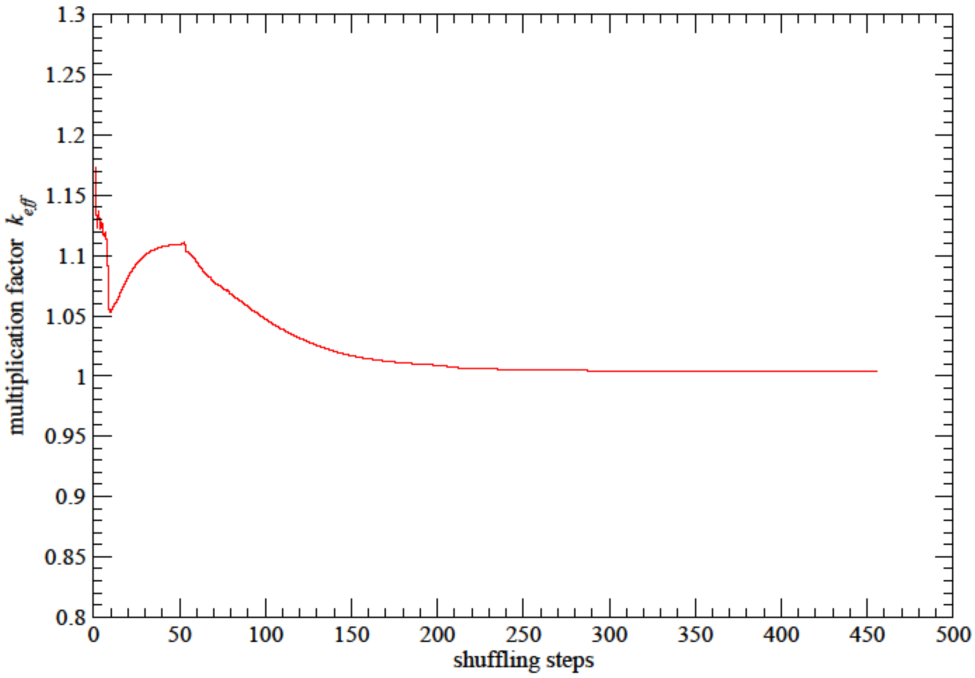

Figure 5: Progress of the multiplication factor k_{eff} in the calculation of the equilibrium core.

Table 3 shows the data of two points in time. As a balance has nearly been reached for the first time, the second time, by contrast shows only small changes in multiplication factor and burn-up.

Both the values for the maximum coolant temperature and for the heat taken away do not reach the theoretically expected values (700 *°C*, 10 *MW*). This is due to the fact that when pre-setting the coolant mass flow obviously all the heat produced in the equation for the enthalpy has been received and no heat loss was considered beyond the outer walls.

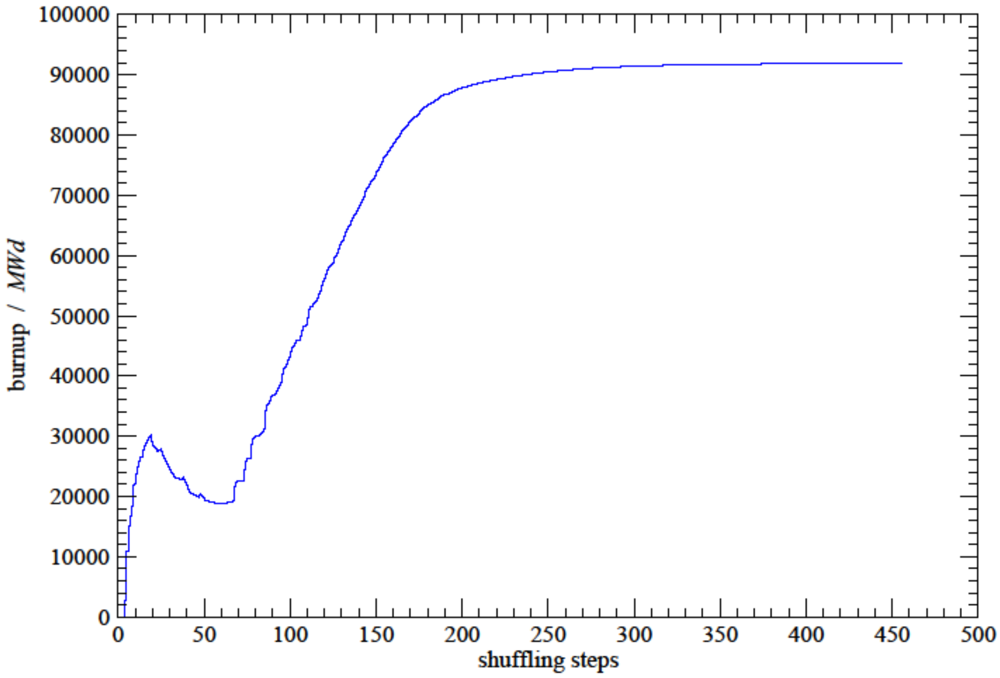

Figure 6: Progress of the burn-up during calculating the equilibrium core.

Table 3: Results of the calculation of the equilibrium core.

shuffling steps	367	456	
operating days	3600	4456	*d*
multiplication factor k_{eff}	1.00401	1.00393	
burn-up	91763	91859	*MWd/t*
max. power density	2.44	2.44	MW/m^3
max. power per fuel element	0.56	0.56	*kW*
gas temperature	250 – 690	250 – 690	*°C*
max. fuel temperature	878	878	*°C*
heat transfer in coolant	9.82	9.82	*MW*

3 Current operating state of the HTR-10

The HTR-10 was only partly in operation during the years 2003-2007. After this time the reactor was out of service [7]. Figure 7 shows the operating days and the power values in this period.

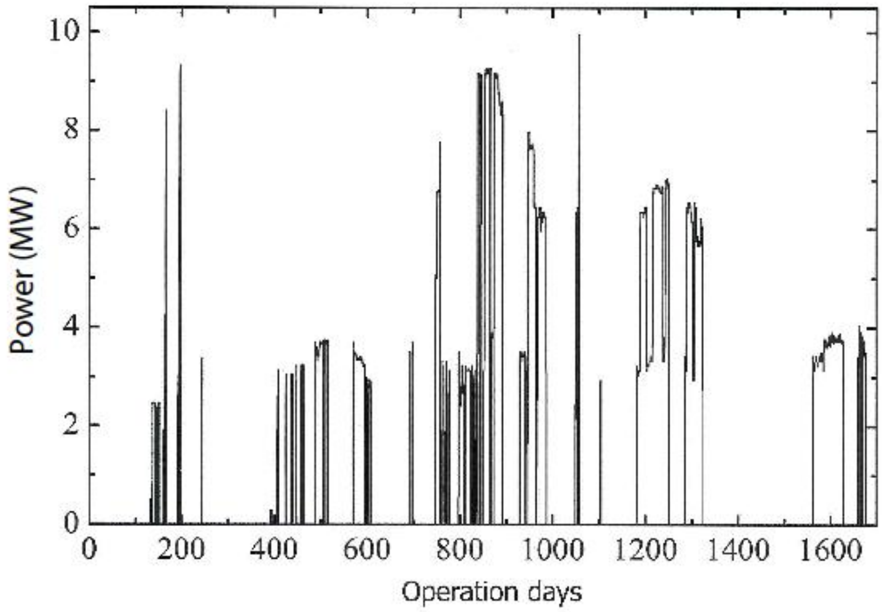

Figure 7: Operation history of the HTR-10 [7].

The average values per year of use are:

Table 4: Operation history, average values per year.
(The data of the left four columns are taken from [7]).

Year	Operation days [*d*]	Average work [*MWd*]	Average power [*MW*]	≙ full power days of the equilibrium core
2003	106	258.9	2.44	25.89
2004	168	708.5	4.22	70.85
2005	149	821.4	5.51	82.14
2006	97	532.0	5.48	53.20
2007	49	182.6	3.73	18.26
				sum: 250.34

Table 4 clearly shows that the equilibrium state of the fuel loading of HTR-10 has not been reached. To get detailed information about the burn-up, a close look at the burning in phase needs to be done. This requires precise knowledge of the loading and shuffling scheme.

Following [2] the transition from the initial core to equilibrium core is divided into 4 phases:

- **Phase 1** The cavity between the pebbles in the reactor core is filled with air, the cone area of the core is filled with dummies. In the cylindrical area the core is filled with a mixture of 57% fuel elements and 43% dummies until the core becomes critical.
- **Phase 2** The air is replaced by helium and the core is completely loaded with the given mixture of fuel and dummy elements.
- **Phase 3** Start of circulation of the fuel. If the first fuel element is discharged, it has been achieved such a
  high burn-up that it can be detected without difficulties.
  This allows the distinction to the dummy elements, so they can be separated and discharged.
  In the next shuffling step the fuel elements will be refilled into the core above.
- **Phase 4** The equilibrium state is reached. This means that depending on the height position burn-up changes not longer during the following shuffling steps.

If this is done according to these phases, the result is an extremely complex loading scheme:

In the first shuffling step all channels are loaded with the fuel-dummy element mixture. At the same time dummy elements are discharged from all channels.

During the second step nothing changes in loading but the first fuel elements from channels 1-3 are unloaded and prepared for the next loading step.

In the third cycle the fuel of channels 1 to 3 are distributed evenly across all 5 channels. This will change for the first time the volume of the upper batches. The contents of 3 batches from the first 3 channels are divided into three batch contents for 5 channels. The missing amount of fuel will be replaced by increasing the batch contents of the other two batches or one of these batches which obtained fresh fuel. Without this split, the surface of the pebble bed would drop.

In the fifth cycle channel 4 discharges fuel for the first time, in the eleventh cycle channel 5 discharges fuel for the first time.

In the 17th cycle (14 regions of channel 1 plus 3 additional cycles) reactive elements are no longer discharged from channel 1 for the first time. This means that in the 18th cycle instead of 3 batches now 4 batches have to be recycled. The contents of the 5th batch will be discharged finally as intended.

By the just described examples, which represent only the initial part of the volume changes of the batches, the situation and in particular the respective additional loading with fresh fuel is constantly changing.

Table 5 shows an example of the different batches of the volume of channel 1 of the first 25 cycles, the above described lack of quantity of fuel will be divided evenly on the batches to be loaded with fresh fuel.

Table 5: Loading and unloading into channel 1.
(numerical values: see Table 1).

channel 1	loading					discharge				
batches	1	2	3	4	5	1	2	3	4	5
1st step	f FE 7426.8	f FE 7426.8	f FE 7426.8	D 7426.8	D 7426.8	D	D	D	D	D
2nd step	f FE 7426.8	f FE 7426.8	f FE 7426.8	D 7426.8	D 7426.8	box 1	box 2	box 3	D	D
						loading: box 1: 7426.8+8096.0+7537.6=23060.4 box 2: 7426.8+8096.0+7537.6=23060.4 box 3: 7426.8+8096.0+7537.6=23060.4				
3rd step	f FE 11929.4	f FE 11929.4	box 1 4425.1	box 2 4425.1	box 3 4425.1	box 1	box 2	box 3	D	D
	23060.4 · 0.19189 = 4425.1 in batch 3 23060.4 · 0.19189 = 4425.1 in batch 4 23060.4 · 0.19189 = 4425.1 in batch 5 37134 - 3 · 4425.1 = 23858.7, divided into batches no. 1 and 2: 11929.4									
4th step	f FE 11929.4	f FE 11929.4	box 1 4425.1	box 2 4425.1	box 3 4425.1	box 1	box 2	box 3	D	D
						loading: box 1: 7426.8+8096.0+7537.6+10252.6=33313.0 box 2: 7426.8+8096.0+7537.6+10252.6=33313.0 box 3: 7426.8+8096.0+7537.6+10252.6=33313.0				
5th step	f FE 8978.4	f FE 8978.4	box 1 6392.4	box 2 6392.4	box 3 6392.4	box 1	box 2	box 3	D	D
	33313.0 · 0.19189 = 6392.4 in batch 3 33313.0 · 0.19189 = 6392.4 in batch 4 33313.0 · 0.19189 = 6392.4 in batch 5 37134 - 3 · 6392.4 = 17956.8, devided into batches no. 1 and 2: 8978.4									
6th step	f FE 8978.4	f FE 8978.4	box 1 6392.4	box 2 6392.4	box 3 6392.4	box 1	box 2	box 3	D	D
7th step	f FE 8978.4	f FE 8978.4	box 1 6392.4	box 2 6392.4	box 3 6392.4	box 1	box 2	box 3	D	D
8th step	f FE 8978.4	f FE 8978.4	box 1 6392.4	box 2 6392.4	box 3 6392.4	box 1	box 2	box 3	D	D
9th step	f FE 8978.4	f FE 8978.4	box 1 6392.4	box 2 6392.4	box 3 6392.4	box 1	box 2	box 3	D	D
						loading: box 1: 7426.8+8096.0+7537.6+10252.6+5390.6=38703.6 box 2: 7426.8+8096.0+7537.6+10252.6+5390.6=38703.6 box 3: 7426.8+8096.0+7537.6+10252.6+5390.6=38703.6				
10th step	f FE 7426.8	f FE 7426.8	box 1 7426.8	box 2 7426.8	box 3 7426.8	box 1	box 2	box 3	D	D
	38703.6 · 0.19189 = 7426.8 in batch 3 38703.6 · 0.19189 = 7426.8 in batch 4 38703.6 · 0.19189 = 7426.8 in batch 5 37134 - 3 · 7426.8 = 14853.6, devided into batches no. 1 and 2: 7426.8									

Table 5: Loading and unloading into channel 1 (cont.).
(numerical values: see Table 1).

channel 1	loading					discharge				
batches	1	2	3	4	5	1	2	3	4	5
11th step	f FE 7426.8	f FE 7426.8	box 1 7426.8	box 2 7426.8	box 3 7426.8	box 1	box 2	box 3	D	D
12th step	f FE 7426.8	f FE 7426.8	box 1 7426.8	box 2 7426.8	box 3 7426.8	box 1	box 2	box 3	D	D
13th step	f FE 7426.8	f FE 7426.8	box 1 7426.8	box 2 7426.8	box 3 7426.8	box 1	box 2	box 3	D	D
14th step	f FE 7426.8	f FE 7426.8	box 1 7426.8	box 2 7426.8	box 3 7426.8	box 1	box 2	box 3	D	D
15th step	f FE 7426.8	f FE 7426.8	box 1 7426.8	box 2 7426.8	box 3 7426.8	box 1	box 2	box 3	D	D
16th step	f FE 7426.8	f FE 7426.8	box 1 7426.8	box 2 7426.8	box 3 7426.8	box 1	box 2	box 3	D	D
17th step	f FE 7426.8	f FE 7426.8	box 1 7426.8	box 2 7426.8	box 3 7426.8	box 1	box 2	box 3	box 4	F
						loading: box 1: 11929.4+8096.0+7537.6+10252.6+5390.6=43206.2 box 2: 11929.4+8096.0+7537.6+10252.6+5390.6=43206.2 box 3: 4425.1+8096.0+7537.6+10252.6+5390.6=35701.9 box 4: 4425.1				
18th step	f FE 12852.5	box 1 8290.8	box 2 8290.8	box 3 6850.8	box 4 849.1	box 1	box 2	box 3	box 4	F
	43206.2 · 0.19189 = 8290.8 in batch 2 43206.2 · 0.19189 = 8290.8 in batch 3 35701.9 · 0.19189 = 6850.8 in batch 4 4425.1 · 0.19189 = 849.1 in batch 5 37134.0 - 2 · 8290.8 - 6850.8 - 849.1 = 12852.5, in batch 1: 12852.5									
19th step	f FE 12852.5	f FE 8290.8	box 1 8290.8	box 2 6850.8	box 3 849.1	box 1	box 2	box 3	box 4	F
						loading: box 1: 8978.4+8096.0+7537.6+10252.6+5390.6=40255.2 box 2: 8978.4+8096.0+7537.6+10252.6+5390.6=40255.2 box 3: 6392.4+8096.0+7537.6+10252.6+5390.6=37669.2 box 4: 6392.4				
20th step	f FE 13229.9	box 1 7724.6	box 2 7724.6	box 3 7228.3	box 4 1226.6	box 1	box 2	box 3	box 4	F
	40255.2 · 0.19189 = 7724.6 in batch 2 40255.2 · 0.19189 = 7724.6 in batch 3 37669.2 · 0.19189 = 7228.3 in batch 4 6392.4 · 0.19189 = 1226.6 in batch 5 37134.0 - 2 · 7724.6 - 7228.3 - 1226.6 = 13229.9, in batch 1: 13229.9									
21th step	f FE 13229.9	box 1 7724.6	box 2 7724.6	box 3 7228.3	box 4 1226.6	box 1	box 2	box 3	box 4	F
22th step	f FE 13229.9	box 1 7724.6	box 2 7724.6	box 3 7228.3	box 4 1226.6	box 1	box 2	box 3	box 4	F

Table 5: Loading and unloading into channel 1 (cont.).
(numerical values: see Table 1).

channel 1	loading					discharge				
batches	1	2	3	4	5	1	2	3	4	5
23th step	f FE 13229.9	box 1 7724.6	box 2 7724.6	box 3 7228.3	box 4 1226.6	box 1	box 2	box 3	box 4	F
						loading: box 1: 8978.4+13004.3+7537.6+10252.6+5390.6=45163.5 box 2: 8978.4+13004.3+7537.6+10252.6+5390.6=45163.5 box 3: 6392.4+4823.8+7537.6+10252.6+5390.6=34397.0 box 4: 6392.4+4823.8=11216.2				
24th step	f FE 11048.5	box 1 8666.4	box 2 8666.4	box 3 6600.4	box 4 2152.3	box 1	box 2	box 3	box 4	F
	45163.5 · 0.19189 = 8666.4 in batch 2 45163.5 · 0.19189 = 8666.4 in batch 3 34397.0 · 0.19189 = 6600.4 in batch 4 11216.2 · 0.19189 = 2152.3 in batch 5 37134.0 - 2 · 8666.4 - 6600.4 - 2152.3 = 11048.5, in batch 1: 11048.5					loading: box 1: 7426.8+13004.3+7537.6+10252.6+5390.6=43611.9 box 2: 7426.8+13004.3+7537.6+10252.6+5390.6=43611.9 box 3: 7426.8+4823.8+7537.6+10252.6+5390.6=35431.4 box 4: 7426.8+4823.8=12250.6				
25th step	f FE 11246.9	box 1 8368.7	box 2 8368.7	box 3 6798.9	box 4 2350.8	box 1	box 2	box 3	box 4	F
	43611.9 · 0.19189 = 8368.7 in batch 2 43611.9 · 0.19189 = 8368.7 in batch 3 35431.4 · 0.19189 = 6798.9 in batch 4 12250.6 · 0.19189 = 2350.8 in batch 5 37134.0 - 2 · 8368.7 - 6798.9 - 2350.8 = 11246.9, in batch 1: 11246.9									

with:
- f FE : fresh fuel elements
- D : dummy elements
- F : fuel finally to be discharged
- box i (i=1, ⋯,4) : fuel depot boxes

In the channels 2 to 5, a similar picture is shown. The different number of regions in the channels is the determining factor.

A correct representation of these relationships is only possible with the aid of a numerical modeling, because an equilibrium state of the feeding of the batch is reached only after several thousand shuffling steps, as shown in Figures 8 and 9.

After 1000 steps, the difference between maximum and minimum values is about 2%. After 2000 steps, the deviation has dropped to 0.2%, after 5000 steps, it reached around 0.02%.

If we follow a different strategy, in which the missing quantity of fresh fuel is added only in one batch and another batch of the original volume is loaded with fresh fuel, the required number of shuffling steps to reach the equilibrium state would be doubled.

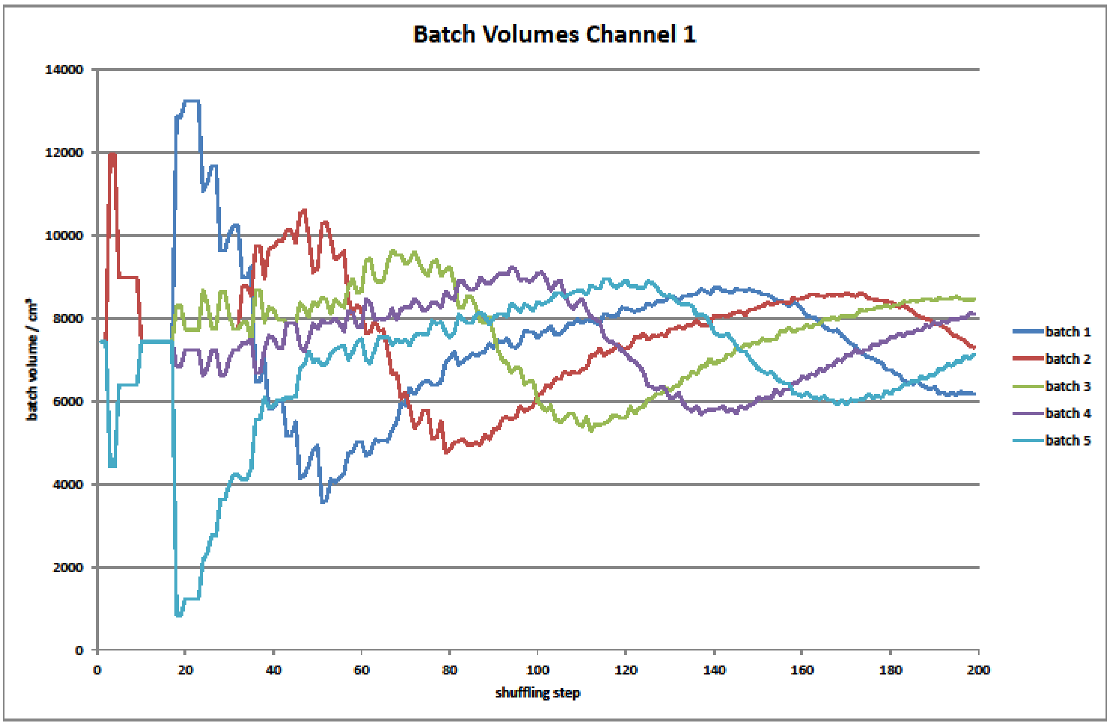

Figure 8: Changes in the batch volume of channel 1 up to the 200th shuffling step.

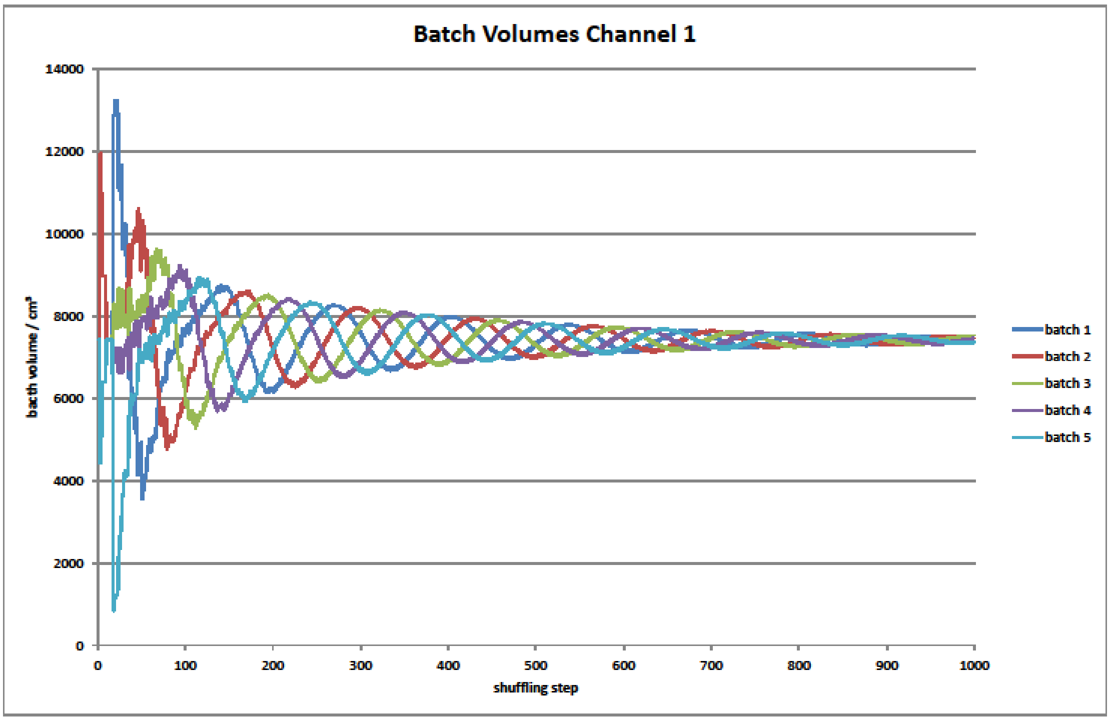

Figure 9: Changes in the batch volume of channel 1 up to the 1000th shuffling step.

4 Summary and outlook

Based on a VSOP input that was used to calculate the initial criticality of HTR-10, a model of the HTR-10 was created for the equilibrium core and calculations have been performed with it.

A mesh grid for calculating the temperature in the solid state and in the cooling gas flow and the calculation of the gas were added to the existing inputs for the pebble bed, a mesh grid and corresponding data for the neutron flux.

Furthermore, a shuffling scheme for loading and unloading fuel elements was modelled. This scheme is based on a core which is in an equilibrium state and therefore the problems discussed in Chapter 3 are not considered.

The results generated by this model agree with the calculated values in [3] and [4] (power density, power of the fuel element, fuel temperature) and show with respect to the requirements, such as burn-up, gas temperature and heat transport 15% higher values.

The current operating situation showed in [7] clarifies that the equilibrium core is far from being reached.
To illustrate the current state correctly, the running in phase should be considered in detail.
This is very expensive due to the relationships described in Chapter 3 and with VSOP in its present form only partially feasible.

It needs to be discussed in the near future which extension of the shuffling scheme should be carried out.

5 Literature

[1] *Evaluation of high temperature gas cooled reactor performance. Benchmark analysis related to initial testing of the HTTR and HTR-10*.
IAEA, IAEA – TECDOC-1382, p.227-253, 2003

[2] **Yongwei Yang, Zhengpei Luo, Xingqing Jing, Zongxin Wu.**
Fuel management of the HTR-10 including the equilibrium state and the running-in phase.
Nuclear Engineering and Design 218, 2002

[3] **Zongxn Wu, Dengcai Lin, Daxin Zhong.**
The design features of the HTR-10.
Nuclear Engineering and Design 218, 2002

[4] **Xingqing Jing, Xiaolin Xu, Yongwei Yang, Ronghong Qu.**
Prediction calculations and experiments for the first criticality of the 10 MW High Temperature Gascooled Reactor-Test Module.
Nuclear Engineering and Design 218, 2002.

[5] **Zuying Gao, Lei Shi.**
Thermal hydraulic calculation of the HTR-10 for the initial and equilibrium core.
Nuclear Engineering and Desgn 218, 2002.

[6] *Evaluation of High Temperature Gas Cooled Reactor Performance. Benchmark analysis related to the PBMR, GT-MHR, HTR-10 and the ASTRA Critical Facility.*
IAEA. Draft of second CRP-5 TECDOC. p 3-18. 2004

[7] **Fu Li.**
The HTR-10 operation performance and data collected.
IAEA Consultancy Meeting. Vienna. 2011.