HTR-N

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High-Temperature Reactor Physics and Fuel Cycle Studies
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Benchmark Problems

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1 INTRODUCTION

Calculations have been performed by NRG-Petten within the framework of the HTR-10 initial core benchmark [1]. The HTR-10 is the Chinese prototype pebble bed gas cooled reactor. For a description and the main data of the reactor, reference is made to the Benchmark Description [1].

2 CODES AND METHODOLOGY

The HTR-10 has been modelled in the PANTHERMIX code [2], a combination of the 3-D diffusion reactor code PANTHER 5.1 [3] coupled to the 2-D thermal hydraulics code THERMIX./DIREKT [4] The nuclear data necessary for the PANTHER code has been generated by means of the WIMS8 [5] code system.

2.1 Cell calculations

Library

The calculations with WIMS8 has been performed with an adapted version of the standard 172 groups 1997 WIMS library based on JEF-2.2. Adaptations has been made for Pu, Am and Cm isotopes to extend the range of temperatures and of the potential scattering to improve the resonance treatment.

Calculational Method

The method followed to overcome the impossibility of modelling the pebbles on coated fuel particle (CFP) scale is to model a cylindrical cell with an equivalent radius. This method has been proved adequate in the PROTEUS benchmark.
The spherical pebble is transformed into an infinite long cylinder but with the same mean chord length. The mean chord length of a concave body is given by the simple relation: 4 times the ration of volume over surface.
So the fuelled part of the pebble (radius 2.5cm) is translated into a cylinder of 1.667 cm radius and contains the fuel kernels, coatings and matrix graphite. This cylinder is surrounded by an annulus of radius 2.191 cm to accommodate the unfuelled shell of 0.5 cm based on conservation of volume ratio. Finally the outer cylinder which contains the admixed moderator pebbles and the void between the pebbles this radius amounts to 3.716 cm in our model. These dimensions and densities are fed into the WIMS module WPROCOL to produce collision probabilities for use in the resonance treatment, for U235, U238 and Pu239 in WRES after an approximate resonance treatment in WHEAD for all other resonant isotopes not treated explicitly in WPROCOL/WRES. This treatment is based on equivalence theory with calculated potential scatter cross section applied on slabs with thickness according to mean chord lengths of the fuel kernel, coatings and matrix graphite belonging to the kernel. In this approximation a Dancoff factor has been used which is derived analytically to account for the double heterogeneity of kernels and pebbles [6]. After smearing and condensation of the pebble and kernel materials to one material and in 16 neutron

energy groups, a pseudo reactor calculation has been started in as well the axial direction (infinite radius) as in the radial direction (infinite length) in the real reactor dimensions. This has been done for the case without control rods (unrodded) and with control rods inserted (rodded).

Three kinds of control rod banks have been used:
a): the normal control rods to govern the power level,
b): the KLAK system for cold shut-down of the reactor and
c): a ‘gas’ control rod bank. This is a control rod bank, which comprises all core channels in the PANTHER model. This bank in the unrodded state returns the nuclear data of the fuel in the unrodded axial meshes of the core, in the rodded state it returns the nuclear data of the Helium void on top of the pebble-bed in the rodded axial intervals. By moving in and out this “gas” rod one can simulate the level of the pebble-bed height in the core. The gas space above the pebble bed has ‘artificial’ and anisotropic diffusion coefficients obtained according to the Gerwin-Scherrer method [7].

KLAK system and control rod calculations have been performed for the radial pseudo reactor calculations by means of the WIMS CACTUS-module (fig. 1). After these pseudo reactor calculations, the materials comprised in the reactor were smeared and condensed into 2 neutron groups, one thermal and one fast neutron group, for the PANTHER full core calculations. The division between the thermal and the fast energy group was at 2.1 eV.

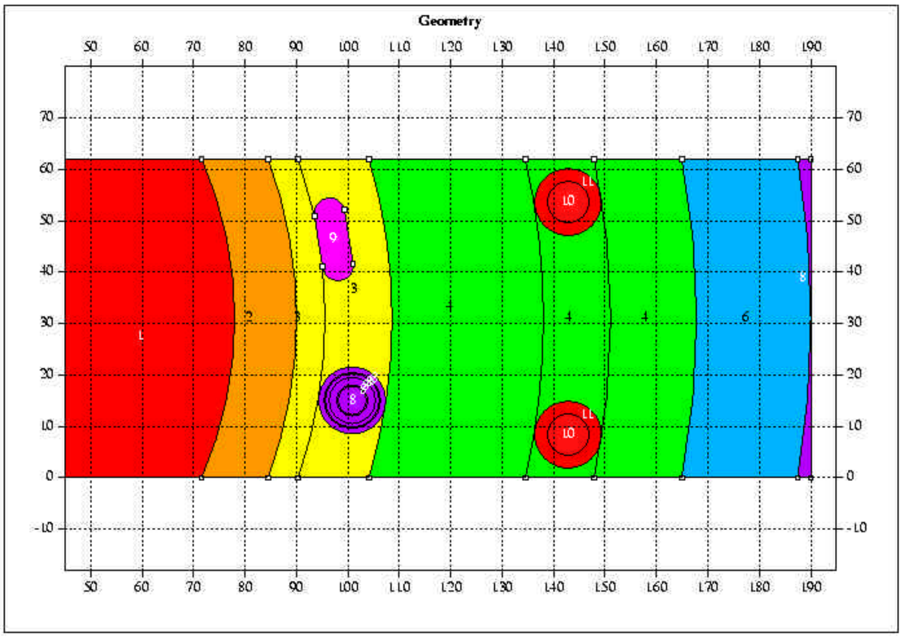


Fig. 1: CACTUS model of control rod holes, KLAK holes and coolant channels. The red and orange areas on the right are part of the core

These pseudo reactor calculations were done for different depletion levels and at different temperatures. This way a database has been constructed, which is temperature, burn-up, control rod and Xenon dependent, in which PANTHER can perform a multidimensional interpolation in the nuclear data, according to the local condition in the reactor.

2.2 Core calculations

PANTHER

The HTR-10 has been approximated in the diffusion code PANTHER in the 3-D X-Y-Z mode with radial 861 square meshes (channels) of 11.48 cm by 11.48 cm and 52 axial intervals of different height but over the core height all 11.10 cm high. The full model comprised 193 core channels, 668 reflector channels, 20 core layers (plus 8 layers to model the bottom cone) 14 bottom reflector layers and 10 top reflector layers. The size of the square mesh has been chosen such that concentric ‘rings’ can be composed from these meshes in a manner that those rings fit snugly with the main radial dimensions of the reactor structures (figures 2, 3 and 4).
Each mesh in the PANTHER model contains a distinct material with a corresponding set of nuclear data. In each mesh the nuclear data will be generated according to the local burn-up, temperature, etc. from the nuclear database to perform a new time step. An algolritm has been added to PANTHER to simulate the flow of the pebbles through the reactor after each time step by means of transfer of basic parameters (local burn-up) to the neighbouring meshes and keeps track of the classes of the local burn-up distribution.

The aforementioned rings do coincide with the radial meshing of the thermal hydraulic code THERMIX part of the PAN(THER THER)MIX code package. They are used to transfer the power distribution from PANTHER to THERMIX and receive back the temperature field from THERMIX.

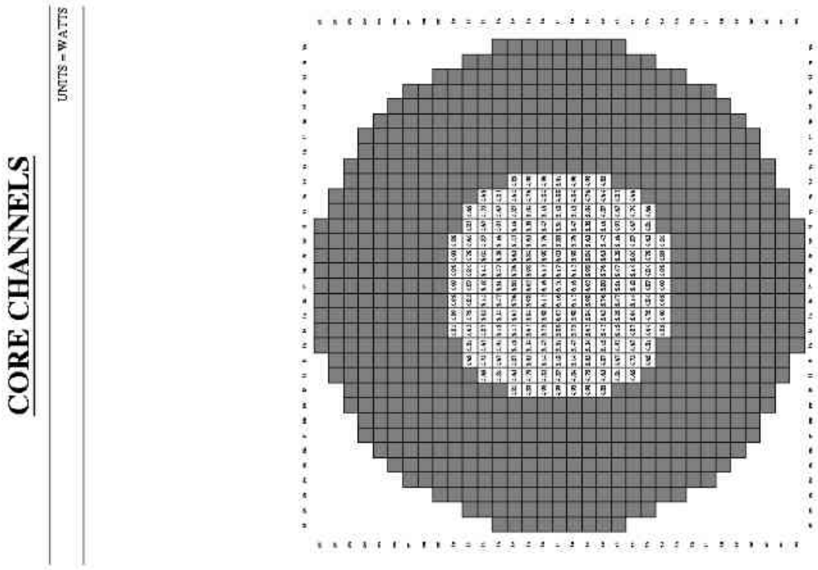


Fig 2: Layout of the core and reflector channels in PANTHER.

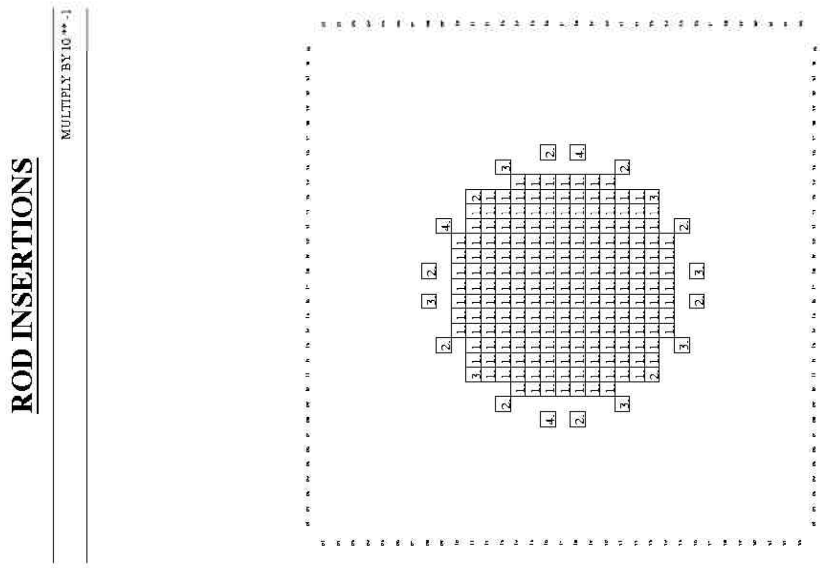


Fig. 3: Layout of the rod types. The "gas"rod bank, which insertion determines the core height, is indicated by a 1, the normal control rods in the reflector are numbered with a 2, the KLAK system by a 3 and the instrumentation channels are designated by a 4.

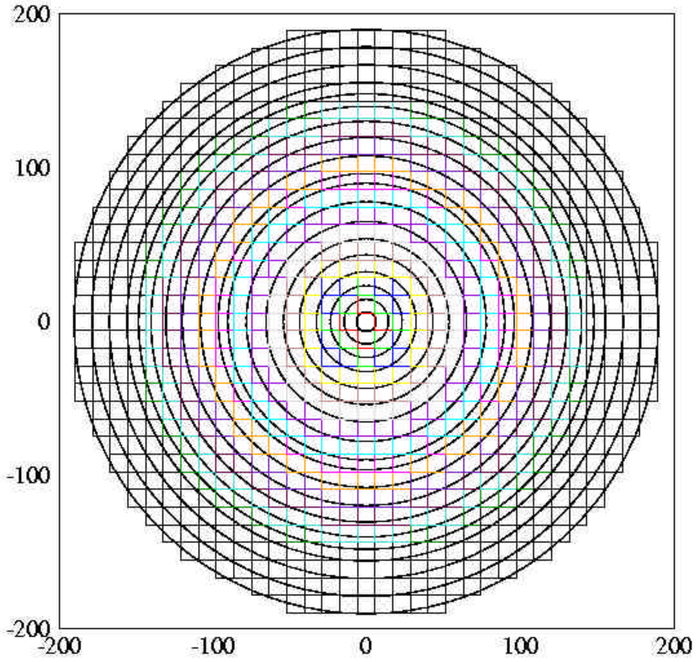


Fig. 4: Reactor channels and assigned rings to correspond with the 2D R-Z THERMIX model.

THERMIX

THERMIX or better the THERMIX/DIREKT code is a 2-D R-Z thermal hydraulics code to calculate the temperature distribution for the solid and gaseous materials in the reactor from a given power distribution (by PANTHER). For the mapping of the 3-D power profile on the 2-D grid of THERMIX the power in the squares which form a 'ring' in PANTHER are radially averaged and transferred to the mesh in THERMIX. For the temperature profile from THERMIX the values for a R-Z set are unfolded to a PANTHER ring. There are 19 radial rings composed in the PANTHER model and 22 radial meshes in the THERMIX model of which the extra meshes do form the boundary conditions. The THERMIX part of the code solves the (time-dependent) equations for the conductive and radiative heat transfer whereas DIREKT solves the (time-dependent) equations for the heat transfer from solid material to the gaseous coolant and the continuity equation of the gas flow. Contrary to the thermal hydraulic options in PANTHER, THERMIX allows for cross channel flows necessary to simulate natural convection in a situation without mass flow.
The complex heat transfer and heat conductivity in the pebble bed is chosen as modelled in THERMIX according to the Zehner-Schlünder method [8].
Thermal data like heat conductivity and heat capacity of the different materials are calculated as function of temperature and pressure according build-in equations. For the graphite the properties of un-irradiated A3 grade have been used.

3 HTR-10 BENCHMARK

3.1 HTR-10 Critical Core Level

Under benchmark conditions, so with an isothermal reactor temperature of 20 °C, the control rods at 114.7 cm and atmospheric Helium in the coolant spaces, a critical search on the core level ('gas'rod insertion) has been performed by PANTHER. The critical core level was found to be:

$$H_{crit} = 125.3 \text{ cm},$$

above the bottom cone filled with moderator balls.

3.2 HTR-10 Iso-thermal Temperature Coefficient

With the reactor at iso-thermal temperatures of 20, 120, 200 and 250 °C and a core height of 180 cm (full core), PANTHER calculated the corresponding multiplication factor.
According to the definition of $\bullet(T) = (k_{T1}-k_{T2})/((k_{T1}*k_{T2})*(T_1-T_2))$we found the following values, listed together with the values as obtained by VSOP at INET (fig.5):

temp(C)	k_{eff} INET	k_{eff} NRG	• (T) NRG	• (T) INET
20	1.119747	1.11759		
120	1.110435	1.10846	-7.37E-05	-7.49E-05
200		1.10115	-7.49E-05	
250	1.095961	1.09629	-8.05E-05	-9.15E-05
		average	-7.64E-05	-8.32E-05

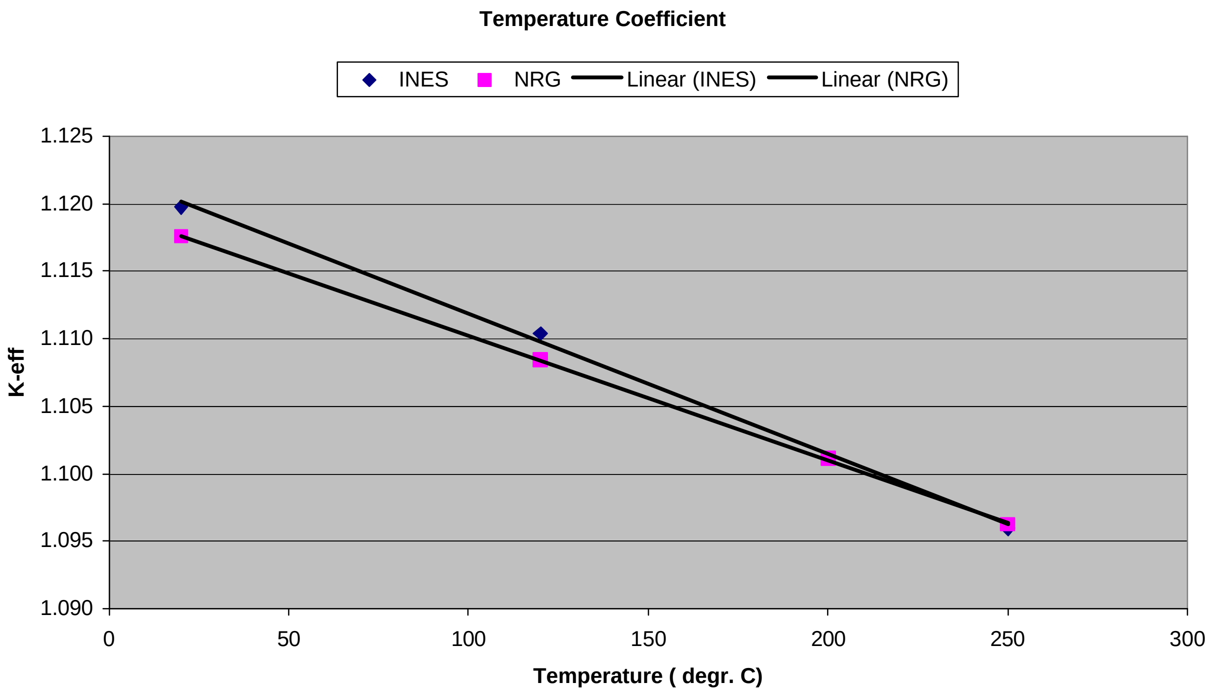


Fig. 5: K-eff as function of an isi thermal temperature over the entire reactor as derived by NRG and INET.

3.3 HTR-10 Scram Reactivity

With the core level at 180.0 cm (full core) and a uniform reactor temperature of 20 °C,
The insertion of the control rods from119.2 cm to 394.2 cm gave rise to a reactivity effect of:

$$\bullet_{scram} = 0.1186.$$

And with the core level at 125.3 cm (critical level) and a uniform reactor at of 20 °C,
The insertion of the control rods from119.2 cm to 394.2 cm gave rise to a reactivity effect of:

$$\bullet_{scram} = 0.1367.$$

This is rather low compared with the measured data of 0.18 (INET) and can probably be explained by strong steaming in the holes to accommodate the control rods and the KLAK system. Recalculations will be done later with modified anisotropic diffusion coefficients according to the Behrens method.

3.4 HTR-10 Control Rod Worth

With the reactor at 20 °C and the core level at 125.3 cm a series of calculations has been done for different insertion fractions of all control rods. Fraction 0 is at the top of the reactor and fraction 1 is at the bottom of the reactor: 610 cm (fig. 6).

rod fract.	rod (cm)	k_{eff}
0.00	0.0	1.00233
0.05	30.5	1.00234
0.10	61.0	1.00219
0.15	91.5	1.00156
0.20	122.0	1.00005
0.25	152.5	0.99342
0.30	183.0	0.98584
0.35	213.5	0.97838
0.40	244.0	0.96887
0.45	274.5	0.94921
0.50	305.0	0.91803
0.55	335.5	0.89298
0.60	366.0	0.88344
0.65	396.5	0.88153

Calculation of the worth for a single control rod is not sensible because in our model, as can be seen from fig. 3, the control rods are on three distinct positions with only the average midpoint radius equal to the stated radius.

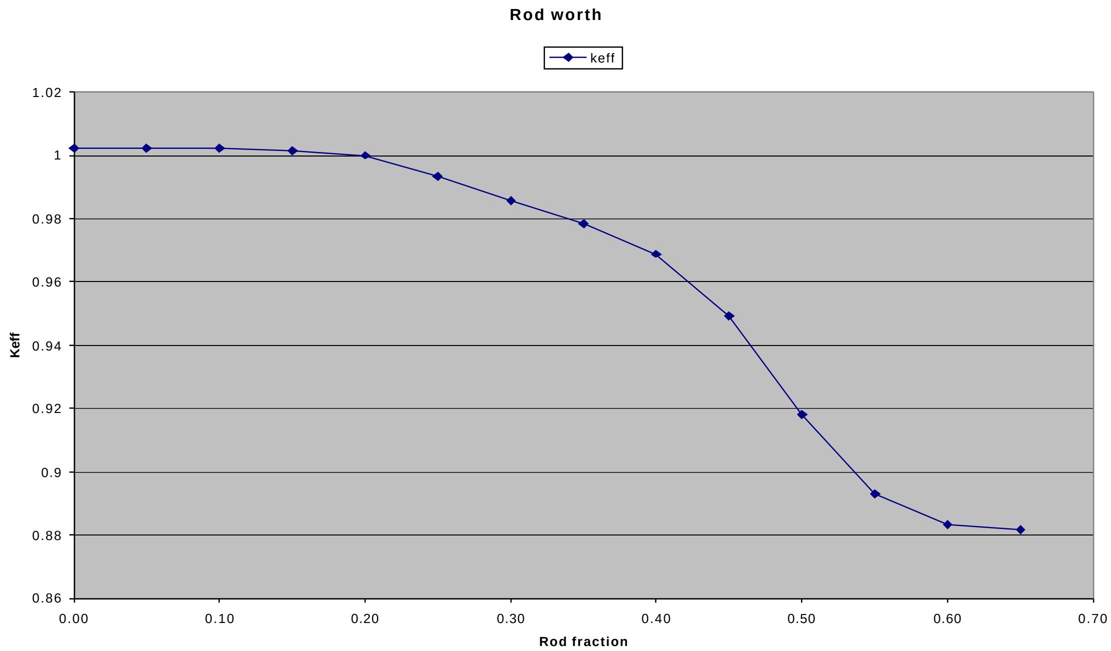


Fig. 6: Reactivity of the reactor as function of the control rod bank insertion for the critical core (core level at: 125.3 cm)

3.5 Full Power Calculations

A thermal hydraulics model has been built to be able to calculate the full power (10 MW) conditions as, flux distributions, power distribution, solid structure temperatures and coolant temperature and mass flow over the reactor. Results for the hot critical initial core (core level at 155 cm) can be seen in figures 7 to 12.

Some key values are:

Maximum pebble temperature	867 •C.
Maximum coolant temperature	804 •C.
Maximum power density	3.41 MW/m^3.
Pressure difference inlet/outlet	0.017 bar.

3.6 Deviated Benchmark

It turned 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

A re-evaluation of the critical core heigth (Hc) has been done by means of the different results for the INET MCNP-calculations for the original benchmark and the deviated one:

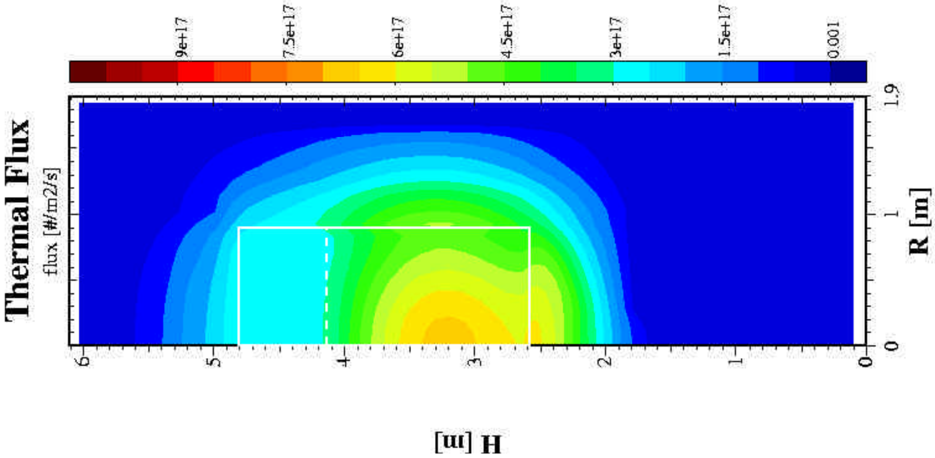
Hc MCNP-INET.

Original	Deviated
126.1 cm	122.9 cm

Hc PANTHER

Original	Deviated
125.3cm	122.1 cm

yielding a good agreement with the measured value of 123.06 cm



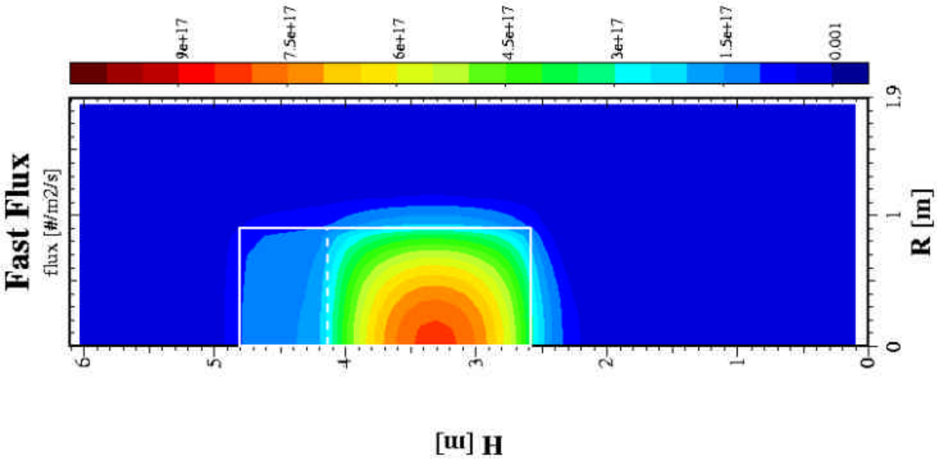
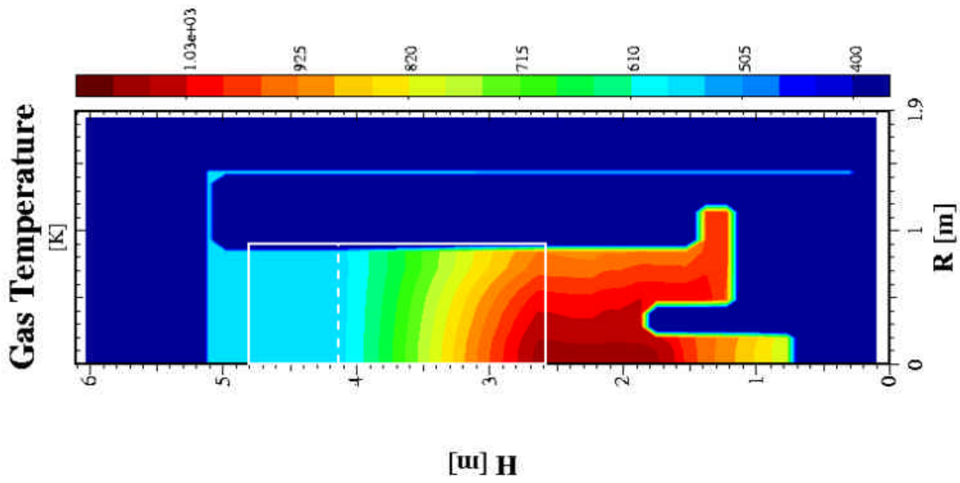
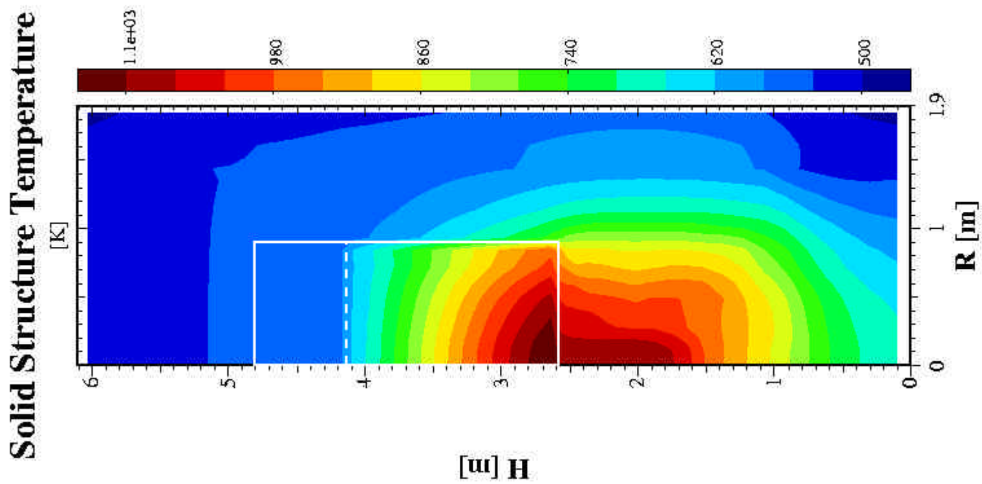
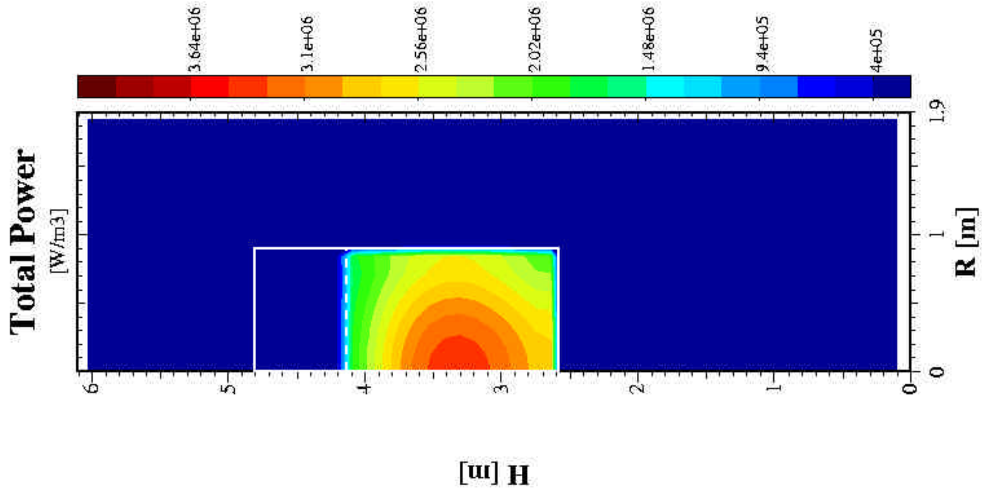


Fig. 7, 8: Thermal and fast flux (fluence rate) over the reactor, white lines indicate the core boundaries whereas the dashed line gives the core level.





*Fig, 9, 10: Temperature distribution for the coolant and reactor structure in degrees **Kelvin**.*



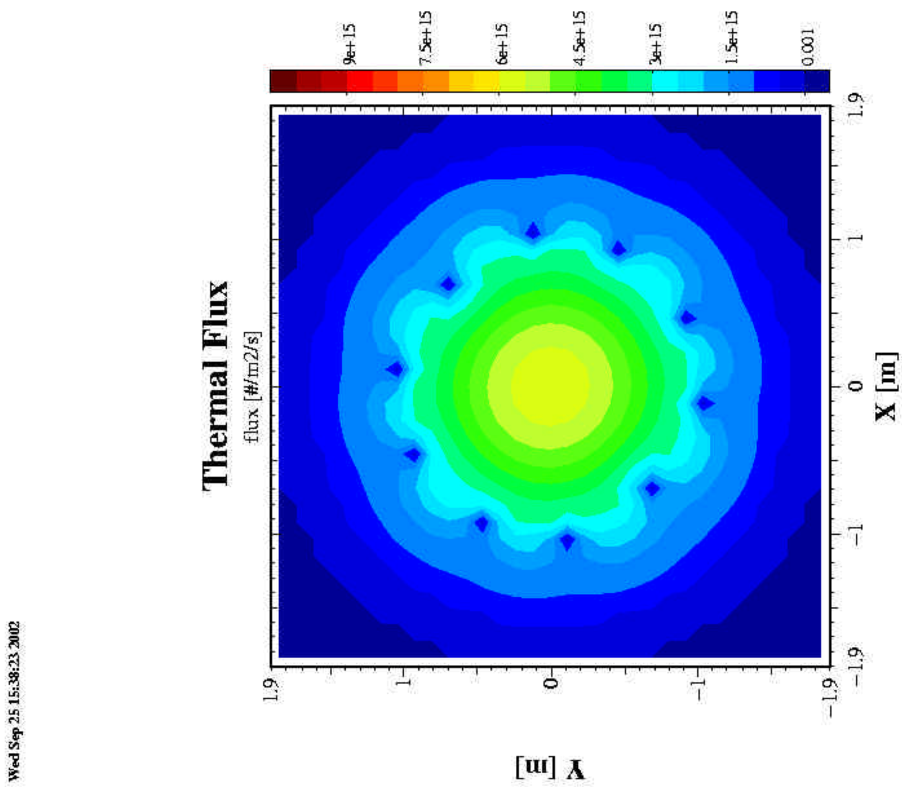


Fig. 11: Power density distribution at full power.
Fig. 12: Radial plot of the thermal flux over the reactor with inserted control rods (arbitrary units)

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