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Document Title

Further Analysis of HTR-PROTEUS Experiments

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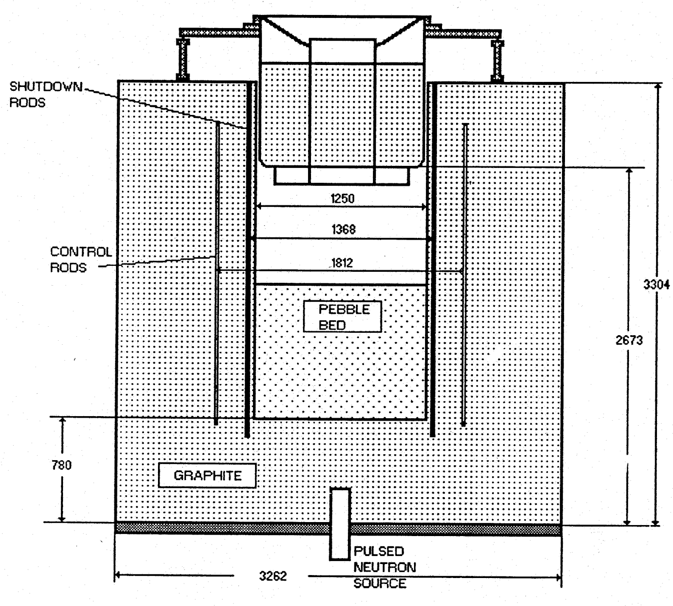
PROTEUS Facility

Benchmark calculations and cold critical experiments for fresh LEU-HTR pebbles (which are now loaded into HTR-10) were done at PSI in the critical facility PROTEUS in the time period 1992-1997 [1]. The main goal of the programme was to provide integral data for small and medium-sized LEU-HTR-systems related to:

- reaction rate distributions and criticality,
- worth of absorber rods which are located in the side reflector,
- the effects of accidental water ingress,
- neutron streaming on the neutron balance.

The experimental results have been analysed mainly with the MICROX-2/TWODANT calculational route. However, some shortcomings especially in calculating the reaction rate traverses have been identified [2]. New calculations with the Monte-Carlo code MCNP-4B have been performed with respect to criticality and reaction rate distributions for two reference core configurations. Monte Carlo calculations with MCNP have already been performed during the HTR-PROTEUS programme, but with poor statistics in the low flux regions (lower and upper reflector). In the meantime, the measurements to estimate the absorption cross-section of the reflector-graphite were re-analysed resulting in an increase of the graphite absorption cross-section from 4.09 to 4.47 mbarn. With new MCNP-4B calculations, the statistical error could be reduced by a factor of two by calculating five million histories.



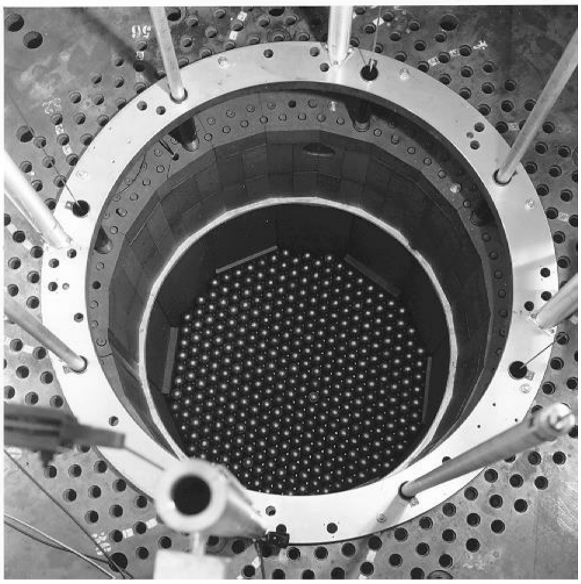


Fig. 1: Vertical cross-section of the HTR-PROTEUS-configuration (dimensions in mm, left) and top view of the pebble-bed (right)

Core Configurations

The cavity was partially filled with mixtures of moderator (pure graphite) and fuel (containing 16.7% enriched UO_2 TRISO-coated particles) pebbles, loaded either in deterministic or random arrangements to form the reactor core. Both pebble types had an outer diameter of 6.0 cm and a fuel region with a diameter of 4.7 cm. The “Arbeitsgemeinschaft Versuchsreaktor” (AVR) in Germany supplied the pebbles. Each fuel pebble contained about 1 g of ^{235}U in ~ 9400 particles.

The presently reported results were calculated for the HTR-PROTEUS Cores 5 and 7. Core 5 has a rhombohedral pebble-lattice geometry with a fuel-to-moderator (F/M) pebble ratio of 2:1, corresponding to a C-to-^{235}U ratio of about 5670. This so-called column hexagonal point on point (CHPOP) pebble-bed arrangement had a filling factor of 0.6046, which is only slightly lower than a stochastic arrangement with a filling factor of 0.62. In order to improve the homogeneity of the core region, an ABCABC … loading scheme was adopted in which the layer pattern repeats every fourth layer. The packing frequency ABC was repeated up to layer 22. Each layer consists of 241 fuel pebbles and 120 moderator pebbles, however the position of the pebbles differed from layer to layer (Fig.2). The arrangement of the 23rd layer (top layer) was changed because too few fuel pebbles remained to form a complete layer. Therefore the remaining 138 fuel pebbles were arranged in a 2:1 lattice in the centre of this layer, with the surrounding area being filled with moderator pebbles.

Core 7 was similar to Core 5 but the vertical channels contained polyethylene rods (total of 654 rods) in order to simulate accidental moderation increase in terms of higher hydrogen density. The pebble-bed core height was reduced from 23 layers to 18 layers to yield a critical configuration. The pebble-layers of Core 7 were identical to those of Core 5 up to layer 17, and the top layer 18 similar to the top layer 23 of Core 5.

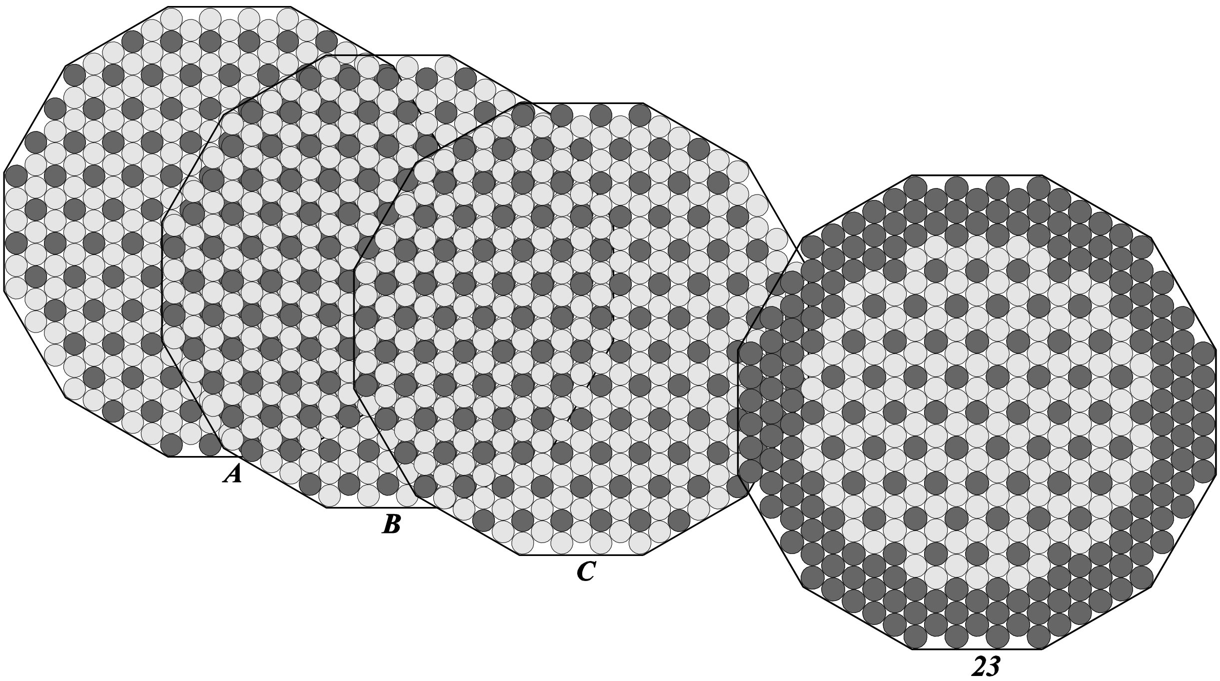
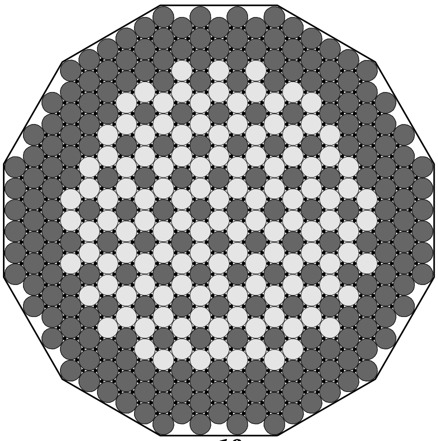


Fig. 2: Pebble Layer Structure of HTR-PROTEUS Core 5 with an ABC, ABC… loading scheme. Only the top Layer (Layer 23) was different. Fuel- (grey) and Moderator-Pebbles (black)



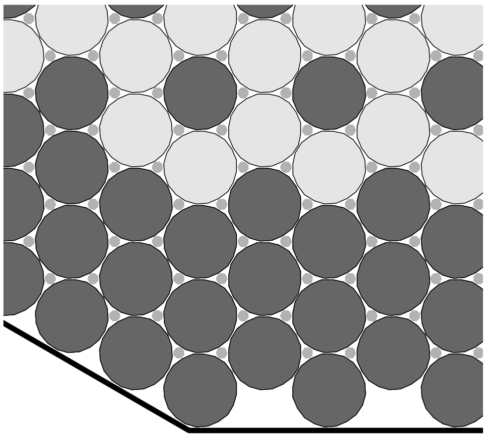


Fig. 3: Structure of top Layer 18 of HTR-PROTEUS Core 7 (left) with Fuel- (grey) and Moderator-Pebbles (black). Enlarged area of top Layer (right) with Polyethylene-Rods in the vertical Channels.

Calculational Methods

The deterministic models for the calculation of Cores 5 and 7 were based on use of the 2-D transport-theory code TWODANT. The necessary macroscopic cross-sections for the doubly heterogeneous pebble-bed-lattices were derived using the MICROX-2 cell code in conjunction with its JEF-1 based data library. Corrections for inter-pebble streaming effects were made, in each case.

The Monte Carlo code MCNP4B was employed along with its ENDF/B-V based continuous-energy cross-section library. For Cores 5 and 7 a very detailed model was developed with the 12-sided polygon, absorber rod channels and the top reflector modelled in detail. Thereby, heterogeneity effects in the core region (particles/matrix/shell for the fuel pebble, moderator/fuel pebble arrangement for the lattice, and polyethylene rods in the case of Core 7) were all treated explicitly. But certain detailed aspects of the HTR-PROTEUS configurations have been omitted in order to facilitate a more straightforward modelling of the experiments. The most important single item, in this context, is represented by the partly inserted control rods which have not been described and had an experimentally determined worth (inserted) of about 84 and 48 cents in Cores 5 and 7, respectively. Considering the other detailed features (e.g. the instrumentation channels, etc.) that have been omitted, one has estimated that corrections of 1109 and 670 pcm (TWODANT) and 834 and 505 pcm (MCNP) need to be applied for the two configurations [3]. The "experimental" k_{eff} values to be used as reference for the presently described TWODANT/MCNP-models for Cores 5 and 7 (without any shutdown rod inserted) are thus 1.0111/1.0083 and 1.0067/1.0051, respectively.

Comparisons with Calculations

Table 1 and 2 show the comparison of calculated and measured values for the system reactivity k_{eff}. As mentioned before, the reactivity was calculated for a system without partially inserted control rods. Only the absorber rod channels and the air gaps of the driver-fuel channels in the side reflector have been modelled for the MCNP-calculations, the experimental k_{eff}-values were corrected accordingly. It can be seen that the calculations agree well with the experiments in Core 7 but underestimate k_{eff} of Core 5. This could be an indication that the polyethylene rods can be smeared into the inter-pebble void, but that streaming corrections, which have to be applied for the core region, are not treated correct in the deterministic model.

Table 1: Calculated and Measured k_{eff} values for Cores 5 and 7

Measured and Calculated k_{eff} Values			
ore	Experimental	TWODANT	MCNP4B
	0111/1.0083±0.0005	0.998	.99502±0.00044
	0067/1.0051±0.0005	1.010	.00268±0.00033

Table 2: Comparison of Calculated and Measured k_{eff} values for Cores 5 and 7

Measured and Calculated/Experimental k_{eff} Values			
ore	Experimental	TWODANT	MCNP4B
	0111/1.0083±0.0005	0.987	0.987±0.00044
	0067/1.0051±0.0005	1.003	0.998±0.00033

A comparison of calculated with experimental axial reaction rate distributions shows a good agreement with MCNP-4B (Fig. 4) and a satisfactory agreement with TWODANT, especially in the low-flux regions (lower and upper axial reflectors). The distributions were normalised to unity in the centre of the pebble-bed.

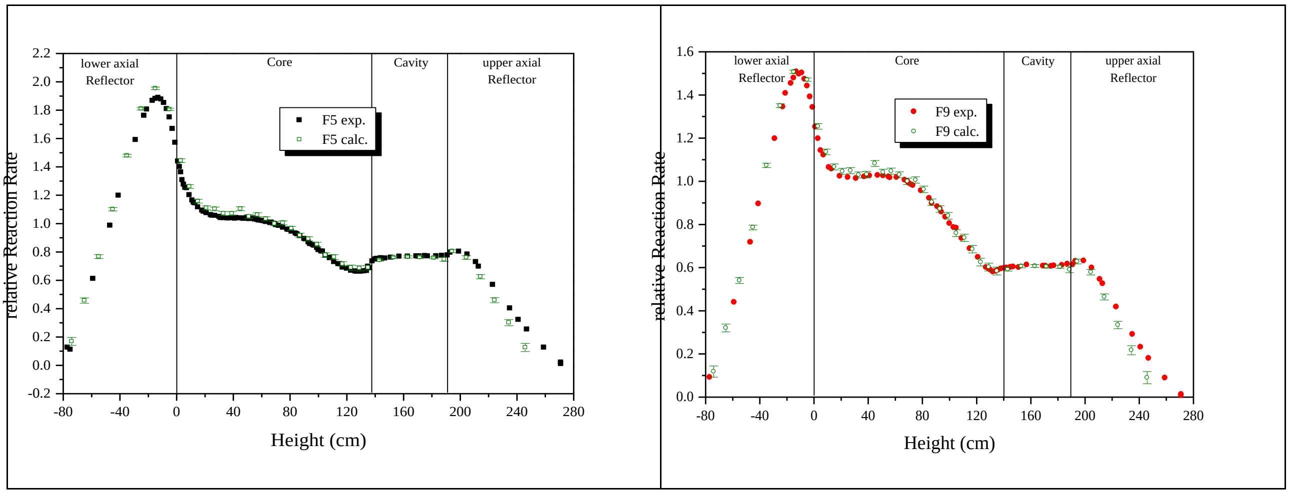


Fig. 4 Experimental and Calculated (MCNP-4B) axial Reaction Rate Traverses of Fission in ^{235}U (F5) and ^{239}Pu (F9) in Core 5.

Conclusions

Deterministic and stochastic calculations have been performed with MICROX/TWODANT and MCNP4B for a core configuration with (Core 7) and without (Core 5) simulated water ingress. The system reactivity (k_{eff}) could be well calculated for Core 7, but was underestimated for Core 5. This can be an indication that water ingress can be well simulated with (heterogeneous) polyethylene rods. The axial reaction rates calculated with MCNP4B are in good agreement with the measurements especially in the lower reflector. The calculations with TWODANT were less satisfactory indicating the need for an exact modelling of the core/reflector region at the bottom of the pebble-bed.

References

1 "Critical Experiments and Reactor Physics Calculations for Low-Enriched High Temperature Gas Cooled Reactors," IAEA TECDOC 1249, IAEA Vienna (2001).

2 O. Köberl, "Experimentelle Neutronenbilanzuntersuchungen zum Wassereinbruch in einen Hochtemperaturreaktor mit niedrig angereichertem Uranbrennstoff'," Thesis N°1803, Swiss Federal Institute of Technology, Lausanne (1998).

3 T. Williams, "LEU-HTR PROTEUS: Configuration Descriptions and Critical Balances for the Cores of the HTR-PROTEUS Experimental Programme," PSI Technical Note TM-41-95-18, Paul Scherrer Institute (1996).