ICNC PROTEUS PBMR MODELLING USING MONK

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Introduction

In order to reduce the design and licensing uncertainties for small and medium sized, highly reflected, helium cooled reactors using low enriched uranium (LEU) and graphite high temperature fuel, a series of critical experiments, in the framework of an IAEA Coordinated Research Programme on "Validation of Safety Related Reactor Physics Calculations for Low Enriched HTRs", was carried out at the zero power facility PROTEUS of the Paul Scherrer Institute (PSI)

This presentation presents the results of the analysis of a series of these PBMR experiments, with different patterns of graphite moderator and fuel spheres. Four cores are of particular interest in the analysis performed here Cores 5, 7, 9 and 10. Cores 5 and 9 are critical assemblies with fuel pebble to moderator pebbles ratios (F:M) of 2:1 and 1:1 respectively. Cores 7 and 10 are modified versions of cores 5 and 9 in which polythene rods have been used to simulate water ingress into the core.

In addition to performing analyses of the critical k-effective, an analysis has been performed of the measured shut-down rod worths. Shut-down rod worths were measured for both single and groups of up to 4 shut-down rods.

Benchmark calculations have been performed using a development version of the Monte-Carlo code MONK (Reference 1), which has an option to model the PROTEUS fuel/moderator geometries. The JEF2.2 nuclear data library has been used for the MONK analyses.

The results from the benchmark analyses are compared with measurement and the results of other participants to the IAEA Co-ordinated Research Programme on "Validation of Safety Related Reactor Physics Calculations for Low Enriched HTRs".

MONK is shown to give good predictive accuracy for PBMR systems for both absolute k-effective values and absorber rod worths.

The technical work described in this paper was undertaken in the period January to March 2006 by staff from Serco Assurance on behalf of NEXIA.

1. Background

In order to reduce the design and licensing uncertainties for small- and medium-sized, highly reflected, helium cooled reactors using low enriched uranium (LEU) and graphite high temperature fuel, a series of critical experiments, in the framework of an IAEA Coordinated Research Programme on "Validation of Safety Related Reactor Physics Calculations for Low Enriched HTRs", was carried out at the zero power facility PROTEUS of the Paul Scherrer Institute (PSI) (Reference 2).

The main objectives of the experiments were to provide high quality experimental data on:

- Criticality of simple, easy to interpret, single core region, LEU HTR systems for several moderator to fuel ratios and several lattice geometries.
- Changes in reactivity, neutron balance components and control rod effectiveness caused by water ingress into the core.
- Effects of boron and/or hafnium absorbers used to modify the reactivity and the power distribution in typical HTR systems.

About 5400 LEU fuel elements, originally manufactured for the German AYR reactor, each containing 6 grams of 16.7% enriched uranium, and 12000 graphite elements, originally manufactured for use in the THTR reactor, were used for the experiments. These spherical elements have an outer diameter of 60 mm. In this benchmark pebble loading arrangements for a range of moderator to fuel pebble ratios were investigated.

2. Measurements

From 1992 to 1996, integral experiments were carried out at the PROTEUS facility comprising investigation of safety-related reactor physics properties of low-enriched Uranium high temperature reactor (LEU-HTR) systems. Various types of experiments have been carried out, in particular, the criticality and reactivity effects of control rods located in the radial reflector and also the effects of water or moisture ingress into these under-moderated cores and the corresponding neutron streaming effects.

Fig. 1 gives a schematic view of the PROTEUS facility (Reference 2). The facility can be described as a graphite cylinder, 3.26 m in diameter and 3.3 m in height, with a central 12-sided polygonal cavity of about 1.20 m in width across flats. This cavity contained the various pebble-bed configurations, which were surrounded by solid graphite reflectors in all directions. The radial reflector contained eight boron-steel safety- and shutdown rods, located symmetrically around the core at a radius of 0.684 m. Four stainless-steel control rods were located at a radius of 0.906 m (Fig. 2). The reactor was operated at room temperature at powers up to 1 kW, so that no active cooling system was required.

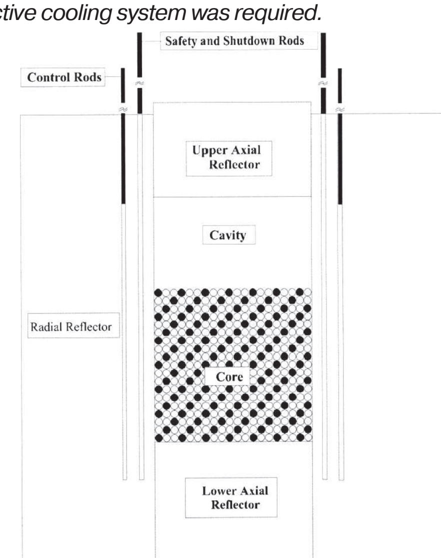

Figure 1 Vertical Section Through PROTEUS Reactor

Figure 2 shows a mid-plane view of the PROTEUS reactor showing a fuel and moderator pebble arrangement and the position of the shutdown and safety rods, located in the radial reflector. In this benchmark, rods no° 5 to 8 are the shutdown rods. For the purposes of the benchmark, the control rod positions are not defined. In the actual experiments the control rods were partially inserted into the radial reflector. Not modelling the control rods will lead to an overestimate in k-effective. The experimenters estimate that excluding the control rods from the modelling will lead to a value of k-effective of approximately 1.08, depending on Control Rod insertion).

A total of 10 different core arrangements were investigated in the course of the HTR PROTEUS experiments. Most of these correspond to deterministic pebble-bed loadings, since these provided well-characterised configurations. The benchmarks studied in this analysis were Cores 5 to 10 which are listed in Table 1.

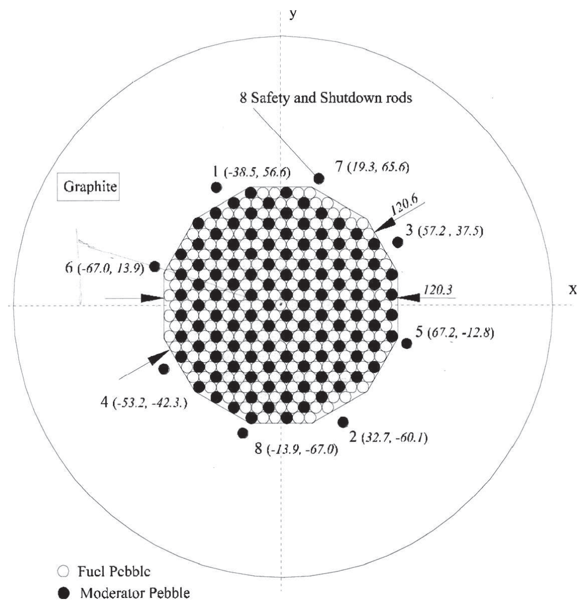

Figure 2 Plan Section Through PROTEUS Reactor Showing Safety and Shutdown Rod Positions

Table 1 PROTEUS Core Configurations 5 to 10

Core Number	Number of Fuel Pebbles (F)	Number of Moderator Pebbles (M)	Ratio Fissile / Moderator	Polyethylene Rods	Comments
5	5433	2870	2.000	No	Layer 1 to 22 with a F/M = 2 Packing Frequency ABC, ABC 23rd layer: FP = 138, MP = 223 NC/NU235: 5667:1
7	4221	2211	2.000	654	Layer 1 to 17 with a F/M = 2 Packing Frequency ABC, ABC 1 8th layer, FP= 130, MP = 231 NC/ NU235: 5700:1 Polythene rods 0.83 cm in diameter, length of 109 cm
9	4509	4877	1.016	No	Layer 1 to 27 with a F/M = 1 Packing Frequency ABCDEF, ABCDEF 28th layer, only Moderator Pebble NC/NU235: 7539:1
10	4332	4332	1.000	654	Layer 1 to 24 with a F/M = 1 Packing Frequency ABCDEF, ABCDEF Nc/Nu235: 7600:1 Polythene rods 0.65 cm in diameter, length of 145 cm

The shutdown rod worths were measured in configurations with column hexagonal point on point (CHPOP) pebble-bed arrangements with filling factors of 0.6046, which is slightly less than the filling factors of random pebble-bed arrangements.

Cores 5 to 8 were configurations with a fuel to moderator pebble ratio (F/M) of 2:1, corresponding to a C-to-235U ratio of about 5670 or a C/U ratio of about 950. Core 7 is in principle a repetition of Core 5, however, water ingress was simulated using interstitial polythene rods. In order to improve the homogeneity of the core region of Core 5, 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. The arrangement of the 23rd layer (top layer) was changed because too few fuel pebbles remained to form a complete 23rd 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..

In Core 7 polyethylene rods were loaded into the vertical channels of the pebble-bed to simulate water or moisture ingress into the core. Due to the increased reactivity of this core with respect to Core 5, its core height had to be reduced significantly to 18 layers.

Core 9 has a F/M ratio of 1:1, corresponding to a C-to 235U ratio of about 7539. In order to obtain a very ho-

mogeneous fuel and moderator pebble arrangement, an ABCDE, ABCDE ... loading scheme was adopted in which the layer pattern repeats every 6 layer. With 27 loaded layers, the system was critical with all control rods fully withdrawn. For the operational loading, an extra layer of moderator pebbles (28th layer) was added to bring the critical control rod position into a convenient range.

Core 10 was a repetition of Core 9, however additional polyethylene rods were loaded and therefore the core height (24 layers) was reduced accordingly.

3. MONK 9 Calculations

The ANSWERS Monte Carlo code MONK (Reference 1) was used to analyse the PROTEUS measurements. A special PROTEUS hole has been written to enable the modelling of the PROTEUS geometries. This enabled precise modelling of the benchmark cores. In order to enable correct modelling of graphite, i.e. bound carbon, the code was run using "BINGO" nuclear data (Nuclear data section of Reference 1).

In order to get sufficient statistical accuracy for Shut-Down Rod (SDR) worth prediction, each case was run to a combined statistical uncertainty on k-effective to at least 0.0004. Each case was run using superhistory tracking (Reference 1) with 1000 neutrons per stage.

MONK has facilities to allow the user to view the model from different directions. This enables accurate checking of the model geometry. Figure 3 shows a slice through Layer A of Core 7, showing the polythene interstitial rods.

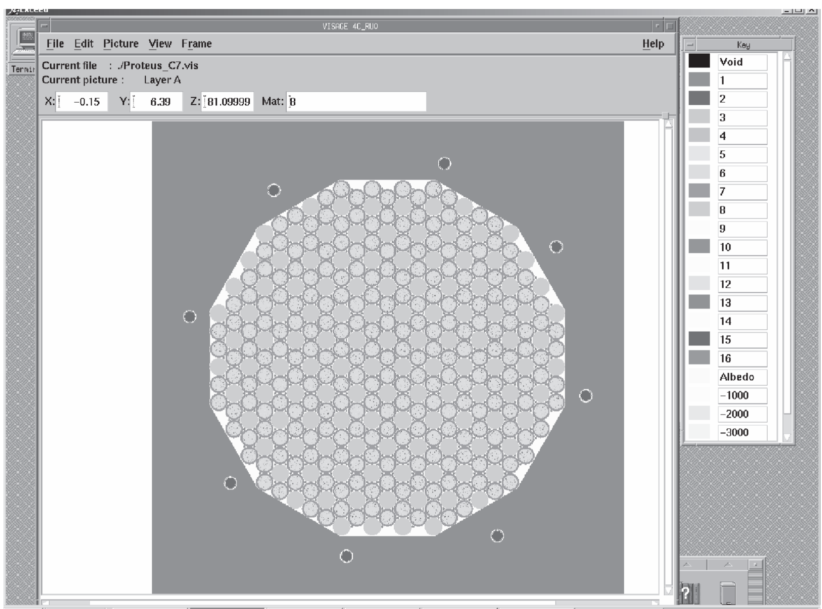

Figure 3 MONK-VISAGE Plot of Layer A of PROTEUS Core 7.

Figure 4 shows the top layer of spheres – Layer 18 in Core 7

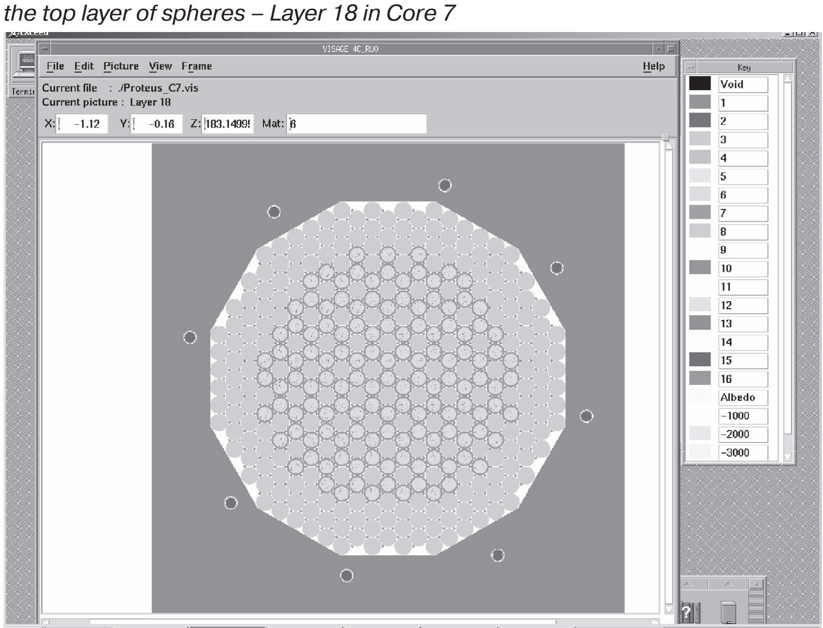

Figure 4 MONK-VISAGE Plot of Top Layer 18 of PROTEUS Core 7.

Figure 5 shows a vertical slice through the model.

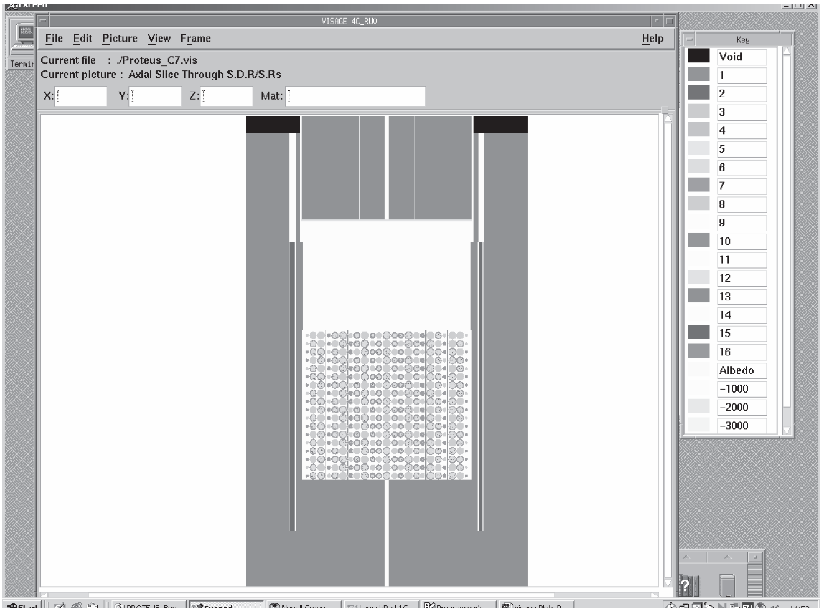

Figure 5 MONK-VISAGE Plot of Vertical Section of PROTEUS Core 7 Showing Inserted SDRs.

Figure 6 shows a close up view of moderator an fuel spheres where the coated fuel particles can be seen.

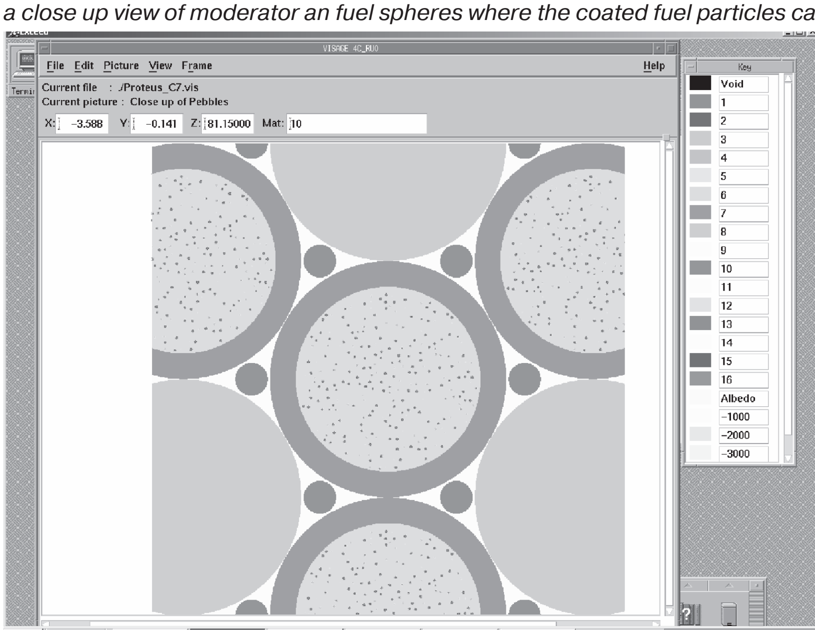

Figure 6 MONK-VISAGE Plot of Close-up Section of PROTEUS Core 7 Showing Moderator and Fuel Spheres.

4. Results of MONK 9 Calculations

The results of the Core Reference k-effective calculations are shown below in Table 2. The results of the calculations show quite good agreement with the suggested experimental values. It should be noted that the partially inserted control rods are not modelled in the Reference 1 benchmark, leading to an over-prediction of k-effective. The results of the MONK reactivity worth calculations for groups of SDRs are shown in Table 3. The results show a tendency to underpredict the SDR reactivity by up to 0.4$. This is roughly proportional to the number of SDRs inserted. The PSI worths for graphite filled channels are based on calculation.

Table 2 Results of MONK k-effective calculations for rods withdrawn Cores 5 to 10.

Core	K-effective	Standard Deviation	Experimental Value
Core 5	1.0112	0.0004	~ 1.008
Core 7	1.0088	0.0004	~ 1.008
Core 9	1.0095	0.0004	~ 1.008
Core 10	1.0059	0.0004	~ 1.008

Table 3 Results of MONK SDR Worth Calculations, in $, Cores 5 to 10.

Core	SDR 5 Inserted		SDRs 5 & 6 Inserted		SDRs 5, 6 & 7 Inserted		SDRs 5, 6, 7 & 8 Inserted	
	MONK	EXPT	MONK	EXPT	MONK	EXPT	MONK	EXPT
Core 5	-3.45	-3.57	-7.25	-7.50	-11.04	-11.45	-15.16	-15.13
Core 7							-9.11	-9.50
Core 9	-3.68	-3.68	-7.62	-7.85	-11.57	-11.61	-16.01	-16.43
Core 10	-2.46	-2.61	-5.39	-5.52	-8.20	-8.63	-11.20	-11.76

Note: The statistical uncertainty on the MONK reactivities is 0.08$.

5. Concluding Comments

A description has been given of a series of experiments with different patterns of graphite moderator and fuel spheres in the PROTEUS facility. In addition, a description of calculations performed on the PROTEUS PBMR benchmark critical and rod worth experiments made at PSI in Switzerland.

In addition the worths of groups of up to 4 shutdown rods have been calculated. The benchmark calculations have been performed using a development version of the Monte-Carlo code MONK 9, which has an option to model the PROTEUS fuel/moderator geometries, and the WIMS deterministic code scheme.

The benchmark calculations using MONK with the BINGO nuclear data library gave good predictions of the critical assembly k-effective and rod worths. The calculations tended to underpredict the reactivity worth of inserted rod banks with a four rod group inserted. MONK appears to underpredict the worth by about 0.34$.

References

1. *ANSWERS Software Service MONK User Guide. SERCO Assurance Winfrith.*
2. *O.Köberl & R.Seiler, “Specification for an Experimental Benchmark on Absorber Rod Worths in LEU-HTR PROTEUS Configurations” WPRS_Benchmark_PROTEUS_V6 (2006-Draft).*