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Abstract

The HTR-10 is a small (10 MWt) pebble-bed research reactor intended to develop pebble-bed reactor (PBR) technology in China. It will be used to test and develop fuel, verify PBR safety features, demonstrate combined electricity production and co-generation of heat, and provide experience in PBR design, operation, and construction.

As the only currently operating PBR in the world, the HTR-10 can provide data of great interest to everyone involved in PBR technology. In particular, if it yields data of sufficient quality, it can be used as a benchmark for assessing the accuracy of computer codes proposed for use in PBR analysis. This paper summarizes the evaluation for the International Reactor Physics Experiment Evaluation Project (IRPhEP) of data obtained in measurements of the HTR-10's initial criticality experiment for use as benchmarks for reactor physics codes.

KEYWORDS: HTR-10, pebble-bed reactor, criticality, research reactor, benchmark evaluation, Chinese reactor

1. Introduction

The International Reactor Physics Experiment Evaluation Project (IRPhEP) is a program of the Nuclear Energy Agency (NEA) of the Organisation for Economic Cooperation and Development (OECD). The Idaho National Laboratory (INL) is responsible for overall technical coordination. The IRPhEP charter is to collect and evaluate data on all sorts of nuclear reactors and critical facilities for the purposes of preserving the data and assessing their quality for use in benchmarking reactor physics computer codes. Reports for the IRPhEP conform to a tightly defined format, which includes four principal parts: a description of the system and the experiments performed on it, an uncertainty analysis to judge how accurate one may regard the results of the experiments to be, one or more "benchmark models" comprising geometric and material descriptions that can be applied in reactor physics computer code input files, and the results of calculations by such computer codes. This paper is a summary of an IRPhEP evaluation of the initial criticality measurements of the Chinese HTR-10 experimental pebble-bed reactor.

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Because the HTR-10 is part of a program that may reach commercial development, rather than a typical benchmark facility intended to enrich the knowledge of the international reactor physics community, much of the information on the HTR-10 is proprietary. All the descriptive data obtained for the IRPhEP evaluation were obtained from published documents, mainly two IAEA TECDOC reports.[1,2]

The IRPhEP evaluation of the HTR-10 is a lengthy document, and this summary does not attempt to condense all the information in the evaluation into a few pages. For the details, the reader may refer to the evaluation report itself.[3] Here, the benchmark models are merely sketched, the results of the computer analyses of the benchmark models are given, and the uncertainty analysis is discussed. The answer to the central question of the evaluation – whether the data provided in publicly available documents on the HTR-10 are suitable for use in benchmarking computer codes – is affirmative: the calculated uncertainty in k_{eff} is about 0.006, but the actual uncertainty is probably considerably less.

2. The Benchmark Models

The HTR-10 is located at the Institute of Nuclear Energy Technology (INET), a unit of Tsinghua University, near Beijing. The HTR-10 project was approved by the Chinese State Council in March 1992, ground was broken in 1994, and construction was completed in 2000. Initial criticality was achieved on 1 December 2000. The purpose of the HTR-10 is to test and develop fuel, verify PBR safety features, demonstrate combined electricity production and co-generation of heat, and provide experience in PBR design, operation, and construction.

Like any PBR, the HTR-10 is fueled by billiard-ball-size spheres containing TRISO-coated fuel particles embedded in a graphite matrix. During reactor operation, the pebbles are introduced at the top and slowly flow downwards through the core region. The HTR-10 core is a cylindrical cavity above a conical zone (the "conus") that funnels pebbles into a discharge tube. The core, conus, and discharge tube are surrounded by graphite blocks (the reflector), most of which contain boron and some of which are penetrated by various borings for coolant flow, control rods, emergency shutdown absorber balls, and other purposes.

In operation at power, the HTR-10 is cooled by helium and the fuel cycle follows a multipass strategy. But in the initial critical experiment, the reactor void spaces were filled with moist ambient air (15 °C and 0.1013 MPa) and the fuel was stationary. The initial fuel loading comprised a mixture of fuel pebbles and "dummy" pebbles (solid graphite) in the core in a ratio of 57:43; the conus and discharge tube contained only dummy pebbles. Pebbles were dropped into the core space in this ratio until the reactor became critical. During this initial fuel loading, pebbles were not removed at the bottom, so the pebbles remained stationary after they settled into position in the core. A small Am-Be source (4.4×10^7 neutrons/s) was provided to assist startup, and the neutron flux was tracked by three neutron counters in the side reflector. The reciprocal multiplication factor N_o/N was obtained from the counting rate as a function of the number of pebbles in the core. Criticality, identified when N_o/N reached zero, was achieved when 16,890 pebbles (fuel and dummy) had been loaded. This is equivalent to a level core height of 123.06 cm.

Prior to the actual initial criticality experiment on the HTR-10, the INET invited the international reactor physics community to participate in a benchmark exercise in which each participant, using its own computational tools, would predict the critical loading of the reactor. For this purpose, the INET provided a geometric model and compositional data for the reactor, which are given in Ref. 1. This information was the basis for the benchmark models in the IRPhEP evaluation.

Two benchmark models were defined for the evaluation. The first model, called the high-fidelity model, is suitable for use in codes that can represent complex geometries accurately, using such methods as combinatorial geometry. The second model, called the simplified model, is appropriate for *r-z* cylindrical-geometry codes.

Fig. 1 displays the high-fidelity model. It explicitly includes the borings in the graphite reflector for coolant flow, control and experiment rods, and emergency shutdown absorber balls ("KLAK," from the German for small absorber balls). It represents the conus as a cone (although the entry and exit to the conus are curved), and it shows the pebbles on top of the core as a cone, whose angle from the horizontal was calculated to be 19.5° by a discrete-elements-method code developed at the INL. (The cone angle was not measured in the experiment.) It also shows the individual pebbles in the core. Not shown, but a part of the high-fidelity model, is the representation of the TRISO particles explicitly.

The atomic number densities of all the regions shown in Fig. 1 are provided in Ref. 1. Most of the densities can be verified from raw compositional data also provided in Ref. 1.

Fig. 2 displays the simplified model. It is axisymmetric (the borings are homogenized in the zones where they are located), and the top of the core is modeled as a horizontal plane. Furthermore, the core is homogenized. The atomic number densities of the reflector zones in the simplified model are also given in Ref. 1. The homogenized atomic number densities in the core were calculated in the IRPhEP work.

3. Results of Computer Calculations

Three computer codes were used to analyze the benchmark models numerically. The high-fidelity model was analyzed by the Monte Carlo code MCNP.[4] The simplified model was analyzed by MCNP, and also by the discrete ordinates code TWODANT [5] and the INL's diffusion-theory pebble-bed reactor physics code PEBBED.[6] Cross sections for TWODANT and PEBBED were calculated for a unit cell model by the INL cross-section processing code COMBINE.[7] In the computational models for

TWODANT and PEBBED, the additional simplification was made of representing the sloping surface of the conus by stair-steps.

In the high-fidelity MCNP model, the random arrangement of the pebbles is represented approximately. Construction of the core model was begun by specifying a regular array of pebbles; then pebbles were removed randomly and remaining pebbles were shifted locally until the proper number of pebbles and packing fraction were achieved.

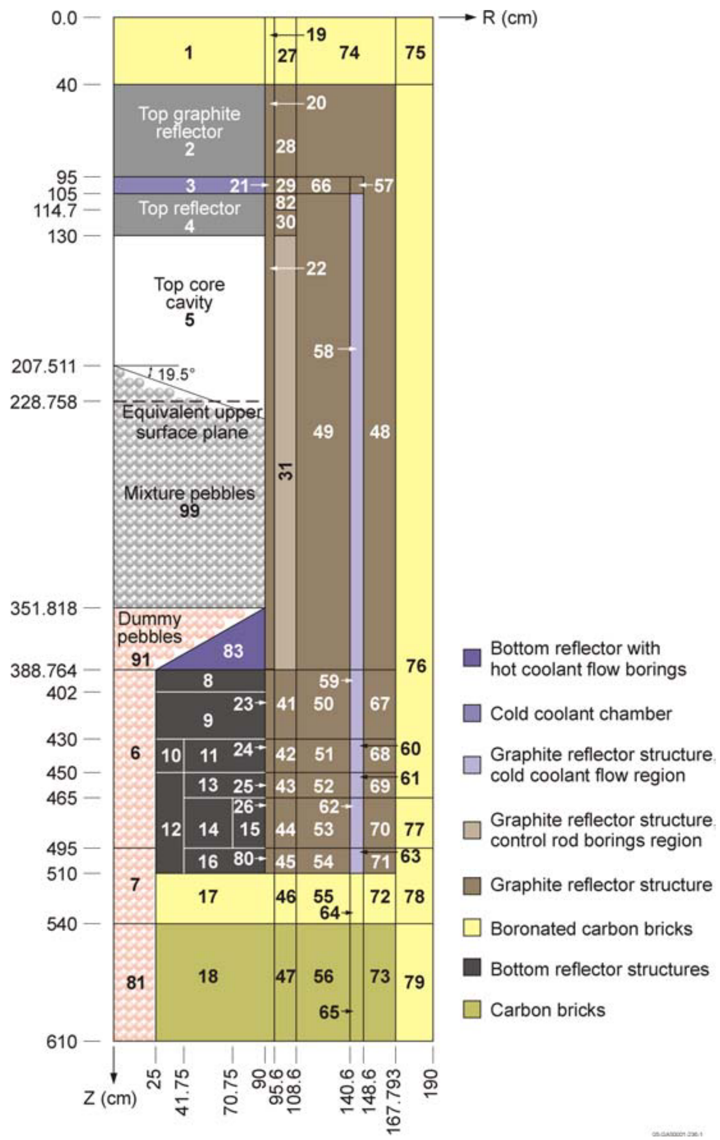
Tab. 1 presents the results of the code calculations for the two benchmark models. The differences among the values in the table are quite large. The difference between the expected benchmark value and the Monte Carlo result for the high-fidelity model is about 1%. It is speculated that the discrepancy may arise from the not-truly-random arrangement of pebbles in the MCNP model. Also, part of the discrepancy could be due to a difference in the actual packing fraction in the experiment (which was not measured) from the nominal value of 61%.

The expected benchmark value for the simplified model is obtained from the difference between the high-fidelity and simplified model Monte Carlo results. This is considered to be the bias introduced by the simplifications in the simplified model. The 30-group discrete ordinates result for the simplified model is close to the expected benchmark value for the simplified model, whereas the six-group results for the discrete ordinates and diffusion models are farther from the expected value but fairly close to each other. This suggests that the further deviation from the expected benchmark value in the six-group models is due to inaccuracies in the cross sections.

The international benchmark exercise sponsored by the INET in advance of the initial criticality of HTR-10 yielded predictions of initial critical core height that were equivalent to values of k_{eff} between 0.952 and 1.044, obtained with a variety of computational tools applied to the same model specifications. Those results, together with the results presented here, suggest that reactor physics analysis in PBRs is far from a well-established art.

Table 1: Code calculations of k_{eff}

Case	$\mathbf{k_{eff}}$	**100(C-E)/E**
High-fidelity model		
Expected benchmark value (experimental results)	1.00000	0.000
Monte Carlo result	1.01190±0.00021	1.190
Simplified model		
Expected benchmark value	1.0131± 0.000297	0.000
Monte Carlo result	1.02500±0.00021	1.175
Discrete ordinates result (30-group)	1.0144	0.128
Discrete ordinates result (B-3, S-16, 6-group)	1.02023617	0.704
Discrete ordinates result (P-1, S-8, 6-group)	1.02028653	0.709
Diffusion result	1.02310	0.987



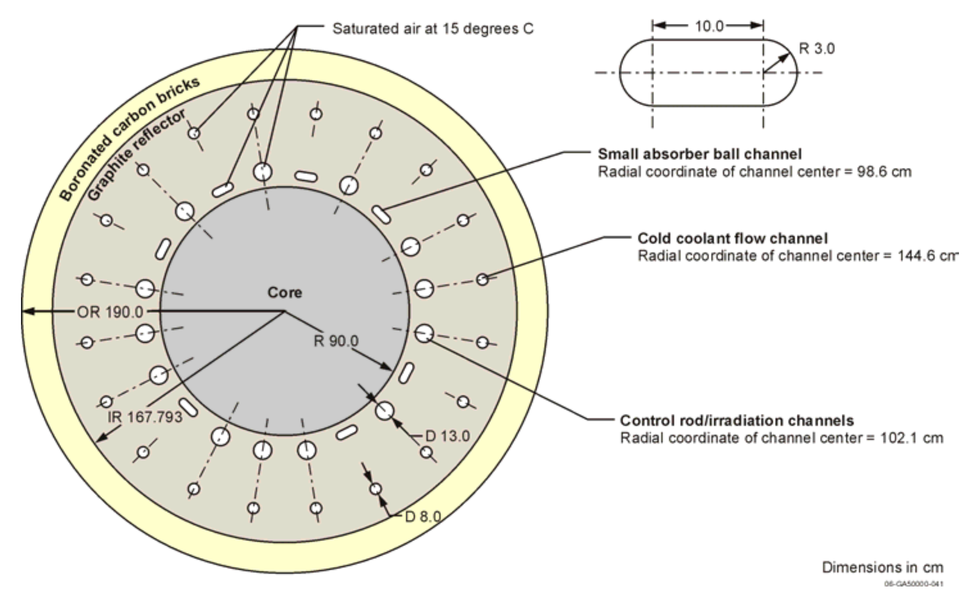


Figure 1: High-fidelity HTR-10 benchmark model

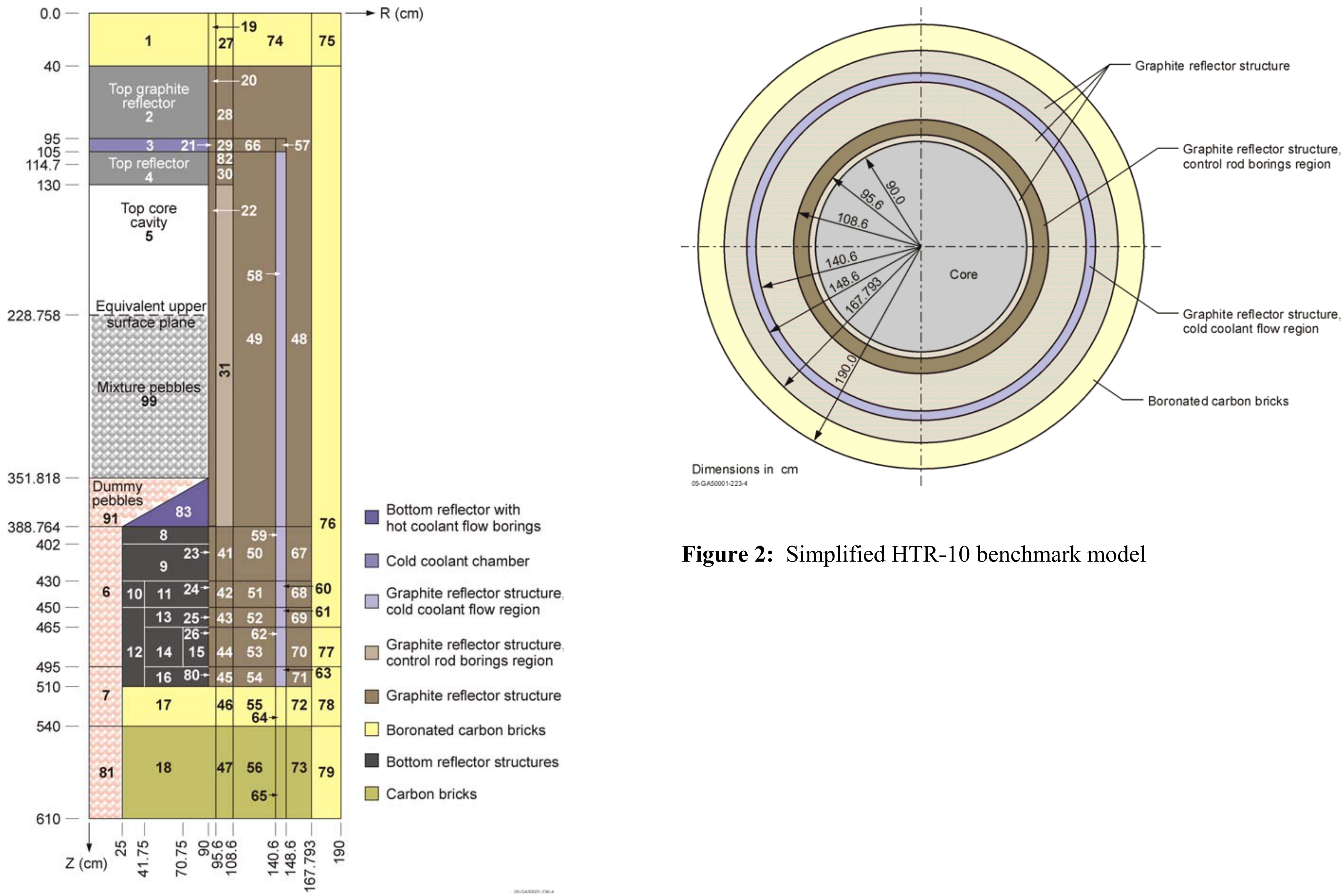


Figure 2: Simplified HTR-10 benchmark model

4. Uncertainty Analysis

Every dimension and composition of any manufactured object or system is subject to uncertainties from manufacturing tolerances, measurement inaccuracies, and other familiar sources. The overall uncertainty in k_{eff} from the combined effects of all these sources is given by [8]

$$u_c^2(k_{eff}) = \sum_{i=1}^{N} (\Delta k_i)^2 + 2\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} (\Delta k_i)(\Delta k_j) r_{i,j} \quad ,$$

where Δk_i is the change in k_{eff} when parameter i is changed by the increment σ_i, the standard deviation in the parameter, and $r_{i,j}$ is the correlation coefficient for parameters i and j.

This expression for the uncertainty in k_{eff} can be evaluated accurately only when the standard deviations in the parameters on which k_{eff} is dependent are known. Because the HTR-10 was not intended for benchmarking purposes, the uncertainties in many of the quantities that can affect k_{eff} have not been reported. Therefore, very conservative assumptions were made in estimating plausible uncertainties in such parameters. For example, in reality most uncertainties have a deterministic component and a random component. However, for components present in large numbers, such as the TRISO particles and the pebbles, the random uncertainties are extremely small (in proportion to the inverse square root of the number of particles or pebbles). Since the division between the deterministic and random components is not known, it was assumed for conservatism that all uncertainties are deterministic. It was assumed that the individual contributions to the total uncertainty are uncorrelated.

Tab. 2 presents a list of all the sources of uncertainty in k_{eff} that were considered. The nominal and bounding values are also listed, along with the effect on k_{eff} of the variation of the parameter to its bounding value. The highlighted entries indicate major contributors to the overall uncertainty.

The table also shows the overall uncertainty in the lower right corner. The value is 0.00624, which is comfortably below 1%. However, the conservatism in the analysis probably leads to a substantial overestimate in the uncertainty. The HTR-10 initial criticality experiment is a useful benchmark for researchers wanting to test criticality codes against real pebble-bed reactor data.

Table 2: Individual and total uncertainties (shaded entries are dominant)

Item	Nominal & bounding values	Uncertainty in k_{eff} (Δk_i) (absolute value)
Core radius	90 cm, +17 pebbles (see text)	1.9e-4
Core height	123.06 cm, +17 pebbles (see text)	3.7e-4
Height of core cavity	221.818 cm, 222.818 cm	2.4e-4
Height of conus	36.946 cm, 39.6815 cm	6.1e-4
Dimensions of graphite blocks	No gaps, gap 1 cm wide at outside of reflector	1.6e-4
Outer diameter of graphite reflector	380 cm, 382 cm	1.0e-4
Height of graphite reflector	610 cm, 616.1 cm	1e-5
Diameter of cold coolant flow channels	8.0 cm, 8.5 cm	1e-5
Radial location of cold coolant flow channels	144.6 cm, 144.85 cm	0
Height of cold coolant flow channels	405 cm, 415 cm	0
Diameter of control rod and irradiation channels	13 cm, 12.5 cm	3.5e-4
Height of control rod and irradiation channels	450 cm, 452 cm	0
Radial location of control rod and irradiation channels	102.1 cm, 102.35 cm	9e-5
Diameter of KLAK channels (upper)	6 cm, 6.2929 cm	0
Dimensions of KLAK channels (middle)	Area=88.2743 cm^2, 97.1017 cm^2	2.8e-4
Diameter of KLAK channels (lower)	6 cm, 6.2929 cm	0
Dimensions of hot gas duct	D=30 cm, 31 cm; L=100 cm, 119.25 cm	0
Radius of fuel discharge tube	25 cm, 25.25 cm	0
Height of fuel discharge tube	610 cm, 616.1 cm	0
Diameter of fuel pebble	6.0 cm, 5.98 cm	5.0e-4
Diameter of kernel	NA (bounded by fuel loading limit)	NA
Thickness of buffer layer	0.009 cm, .00944 cm	2e-5
Thickness of IPyC layer	0.004 cm, 0.005 cm	2e-5
Thickness of SiC layer	0.0035 cm, 0.00376 cm	1.3e-4
Thickness of OPyC layer	0.004 cm, 0.005 cm	3e-5
Uranium fuel loading	5 g/pebble, 5.05 g/pebble	1.03e-3
Density of graphite matrix in fuel pebble	1.73 g/cm^3, 1.77 g/cm^3	1.13e-3
Total ash in fuel element	NA	NA
Lithium in fuel element	0, 0.3 ppm	1e-5
Boron in fuel element	1.3 ppm, 3.0 ppm	4.29e-3
Density of graphite matrix in reflector	1.76 g/cm^3, 1.78 g/cm^3	6.3e-4
Density of boron in reflector graphite	4.8366 ppm, 5.07843 ppm	2.89e-3
Ratio of O to U in kernel	2.0, 2.01	1e-5
Density of kernel	NA (bounded by fuel loading limit)	NA
Density of buffer	1.1 g/cm^3, 1.07 g/cm^3	3e-5
Density of IPyC layer	1.9 g/cm^3, 2.0 g/cm^3	3e-5
Density of SiC layer	3.18 g/cm^3, 3.23 g/cm^3	1e-5
Density of OPyC layer	1.9 g/cm^3, 2.0 g/cm^3	3e-5
Composition of coolant (saturated vs. dry air)	Saturated, dry	1e-5
Air pressure	0.1013 MPa, 0.104686 MPa	3e-4
Boron in kernels	4 ppm, 4.5 ppm	4e-5
Boron in dummy pebbles	0.125 ppm, 0.1255 ppm	NA
Boron in boronated carbon bricks	3.46349e-3 atoms/b-cm, 3.80984e-3 atoms/b-cm	1.9e-4
Pebble packing fraction	0.61, 0.62	1.9e-3
Angle of upper-surface cone from horizontal	19.5°, 17°, 22°	2.14e-3
Thickness of pressure vessel and "core barrel"	0, 10 cm	1.2e-4
Total (root mean square)	NA	6.24e-3

(NA ⇒ not applicable)

5. Summary

The values of k_{eff} predicted in all the computer calculations, both for the high-fidelity and simplified models, vary considerably among themselves and from the expected benchmark values. The reasons for this are not completely understood, but some possible explanations are suspected. However, the uncertainty analysis shows that the experimental data are adequate in quality for use in benchmarking reactor physics computer codes.

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