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VHTRC TEMPERATURE COEFFICIENT BENCHMARK PROBLEM

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VHTRC Temperature Coefficient Benchmark Problem

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As an activity of IAEA Coordinated Research Programme, a benchmark problem is proposed for verifications of neutronic calculation codes for a low enriched uranium fuel high temperature gas-cooled reactor. Two problems are given on the base of heating experiments at the VHTRC which is a pin-in-block type core critical assembly loaded mainly with 4% enriched uranium coated particle fuel. One problem, VH1-HP, asks to calculate temperature coefficient of reactivity from the subcritical reactivity values at five temperature steps between an room temperature where the assembly is nearly at critical state and 200℃. The other problem, VH1-HC, asks to calculate the effective multiplication factor of nearly critical loading cores at the room temperature and 200℃. Both problems further ask to calculate cell parameters such as migration area and spectral indices. Experimental results corresponding to main calculation items are also listed for comparison.

Keywords: Benchmark, Calculation, Temperature Coefficient, VHTRC, Low Enrich, HTGR, Multiplication Factor, Experimental Value, IAEA

VHTRC温度係数ベンチマーク問題

日本原子力研究所東海研究所原子炉工学部
安田 秀志・山根 剛・佐々 敏信

（1994年9月13日受理）

低濃縮ウランを燃料とする高温ガス炉の炉物理パラメータを核計算コードで計算する場合の精度を検討評価する手段とするため，IAEA協力研究計画（CRP）の活動の一環としてベンチマーク問題を作成した。この問題はピンインブロック型炉心をもつ高温ガス炉臨界実験装置VHTRCに主として4％濃縮ウラン被覆粒子燃料を装荷して実施した炉心昇温実験に基づいて作成した。VH1-HP問題では，ほぼ臨界状態となる常温から200℃までの5段階の温度ステップに対して，それぞれの臨界未満度から温度ステップ間の反応度温度係数を算出することを求めており，VH1-HC問題では常温及び200℃でほぼ臨界になるように燃料装荷量を調節した状態での集合体の実効増倍係数を算出することを求めている。上記両問題ではさらに，移動面積，スペクトル指標等のセル計算の結果を出すことも求めている。比較に供するため，主な計算結果に対応する実験結果も示した。

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(1)Evaluated nuclear data for low enriched uranium-graphite systems

(2)Calculation of effective multiplication factor for different temperatures which yields temperature coefficient through cell and whole reactor calculations.

The calculated multiplication factor can be compared with experimental values listed in tables of this paper.

This benchmark problem was originally distributed only to institutions participating in the IAEA Coordinated Research Programme(CRP) on "Validation of Safety Related Reactor Physics Calculations for Low-Enriched HTGRs". This document aims to open the problem to the public.

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:(2) VH1-HC

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: (2) VH1-HC asks to determine the effective multiplication factor of two nearly critical cores at two temperatures.[3]

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The VHTRC is a graphite moderated critical assembly which has a core loaded with pin-in-block fuel of low enriched uranium and a graphite reflector. A bird's eye view of the assembly is shown in Fig. 1. The assembly has a hexagonal prism shape. The surface of the assembly is covered with 0.5 mm thick Cd sheets as thermal neutron absorber and 10 or 15 cm thick Alumina-Silica fiber blankets as heat insulator. The assembly consists of two axially-jointed hexagonal-prism half assemblies. The structure of the half assemblies are made of graphite blocks supported with steel frames as shown in Fig. 2. A cross section of a graphite block (fuel block) is shown in Fig. 3.

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being paired with a solid graphite rod to make axial length, 120 cm. One fuel rod consists of 20 fuel compacts, one graphite sheath and two graphite end caps as shown in Fig. 4. The shape of fuel compact is hollow cylinder. The fuel compact is made of coated fuel particles uniformly dispersed in graphite matrix. The coated fuel particle is, so called, BISO-type which has two carbon layers on uranium dioxide kernel. The cross section of a coated fuel particle is shown in Fig. 5. There are two types of fuel compacts, B-2 and B-4 which differ essentially in the uranium enrichment. By using separately the two types of fuel compacts, two types of fuel rods, B-2 and B-4 rods, are prepared for the experiments.

The assembly was heated from a room temperature up to 200 ℃ by using cartridge type electric heaters inserted axially in the radial reflector. At the room temperature, the assembly was critical in experiments corresponding to both VH1-HP and VH1-HC problems. In the course of assembly heating, the assembly temperature was kept constant and isothermal condition was realized at several steps of assembly temperature. Subcritical reactivity was measured by pulsed neutron method in the experiment corresponding to VH1-HP, on the other hand, critical point was measured by fuel rod addition and control rod adjustment in the experiment corresponding to the second step of VH1-HC .

4. Model Description

4.1 Assembly

Assembly dimensions are given in Table 1. The core is loaded with fuel rods in the pattern shown in Fig. 6 for both all steps of VH1-HP and the first step of VH1-HC, while for the second step of VH1-HC, the core is loaded in the pattern shown in Fig. 7. The movable and fixed half assemblies are loaded with fuel rods symmetrically. In the whole reactor calculation, the configurations can be well dealt by a three dimensional T(Triangular)-Z model considering the symmetry. However, It can be reduced to a simplified two-dimensional R-Z model by keeping cross sectional area as shown in Fig. 8(a). In the R-Z model, calculation will give about 0.1 % lower values of k_{eff} for VH1-HP and 0.2 % higher values for VH1-HC(200℃) than those by the T-Z model. These evaluations are obtained through the cell calculation by collision probability method and the whole reactor calculation by diffusion theory using SRAC[4] code with an ENDF/B-IV based nuclear data library.

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A cross section of a fuel rod should be modelled as shown in Fig. 4. In this model, being paired with a solid graphite rod to make axial length, 120 cm. One fuel rod consists of 20 fuel compacts, one graphite sheath and two graphite end caps as shown in Fig. 4. The shape of fuel compact is hollow cylinder. The fuel compact is made of coated fuel particles uniformly dispersed in graphite matrix. The coated fuel particle is, so called, BISO-type which has two carbon layers on uranium dioxide kernel. The cross section of a coated fuel particle is shown in Fig. 5. There are two types of fuel compacts, B-2 and B-4 which differ essentially in the uranium enrichment. By using separately the two types of fuel compacts, two types of fuel rods, B-2 and B-4 rods, are prepared for the experiments.

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In the cell calculation, one fuel block can be modelled as a unit cell as shown in Fig. 9. Dimensions of a fuel block are shown in Table 2. On the other hand, one fuel rod with surrounding graphite (one twelfth of a graphite block) can also be modelled as a unit cell as shown in Fig. 8(b). There should be no difference, in principle, between results by the two models. It should be noted that the pitches between fuel rods in a graphite block have a common value, however, they are not equal to the distance between two adjacent fuel rods in neighboring two graphite blocks. The two kinds of heterogeneity, i.e., rod-wise and particle-wise, should be taken into account. The particle-wise heterogeneity can be modelled as shown in Fig. 8(c). If the rod-wise heterogeneity is considered and the particle-wise heterogeneity is neglected, the result will give about 0.8 % lower value for k_{eff}. This difference was also estimated by the SRAC. Dimensions of a graphite sheath and an end cap are listed in Table 3. In Table 4, are shown dimensions and uranium content of a fuel compact. Isotopic abundance of uranium in a fuel kernel is listed in Table 5. In Table 6, are listed the detail of calculated atom densities in the fuel compact. The atom densities of the fuel compact homogenized over particles, matrix graphite and an end cap on the core mid-plane are shown in Table 7. The end cap homogenization effect is estimated to be neglibibly small on k_{eff}. Average number of coated fuel particles in a fuel compact is given in Table 8. Atom densities for graphite assembly and sheath are listed in Table 9. The number of fuel rods in the core is summarized in Table 10.

4.3 Boundary Conditions

In the cell calculation, if a cylindrical or spherical model is employed, the boundary condition should be isotropic reflective, on the other hand, if a hexagonal model is employed, it can be perfectly reflective. In the whole reactor calculation, a vacuum boundary condition should be used at the surface of reflector. The steel frames surrounding the reflector have the effective thicknesses of about 2 cm in the radial direction and 0.4 cm in the axial direction. This effect was estimated to about +0.2 % in k_{eff} and was corrected to the experimental results. Therefore, the benchmark calculation can avoid taking account of this effect.

4.4 Neutron Energy Groups

Number of neutron energy groups is not specified in this benchmark calculation. Thermal cut-off energy should be 0.625 eV to calculate spectral indices.

4.5 Assembly Temperature

The experimental temperatures are also shown in Table 10. All the materials in the assembly can be considered to have a common temperature at each step.

4.6 Effect of Thermal Expansion of Assembly

The thermal expansion effect was estimated from the change of calculated k_{eff} values due to the change of assembly dimension and atomic number density between 300 and 500 K using the linear thermal expansion coefficient of the assembly. The resultant temperature coefficient due to thermal expansion of the assembly was -1.0×10^{-5} Δk/k/℃ . This effect was subtracted from the experimental value of temperature coefficient of reactivity. Therefore, it should be neglected in the benchmark calculations.

4.7 Loading Irregularities

As seen in Fig. 10, there are various structural irregularities in the actual assembly, for example, safety rod insertion holes, heaters, thermocouples, partially inserted control rods, neutron detectors, small gap between two half assemblies. The reactivity effects of such irregularities were independently measured and were excluded from the experimental results. Therefore, in the benchmark calculations, these irregularities should be replaced with graphite, for simplicity.

5. Requested Calculation Results

(1) Unit Cell Results

1) $k_\infty(0)$, i.e., productions/absorptions for buckling $B^2 = 0$.

2) The critical buckling B^2_{crit} and $k_\infty(B^2_{crit})$, i.e., productions / absorptions for $B^2 = B^2_{crit}$.

3) The migration area $M^2 = [k_\infty(B^2_{crit}) - 1] / B^2_{crit}$.

4) Reaction rate breakdown for the $B^2 = B^2_{crit}$ case in terms of fissions, captures and productions for each nuclide with normalization to a total absorption (fissions+ captures) of unity.

5) The spectral indices ρ^{28}, δ^{25} , δ^{28} and C^* for the $B^2 = B^2_{crit}$ case.

The spectral indices should correspond to a thermal cut-off energy of 0.625 eV and are defined as:

ρ^{28} = ratio of epithermal-to-thermal ^{238}U captures,

δ^{25} = ratio of epithermal-to-thermal ^{235}U fissions,

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Items 1) to 3) are to be computed for every step of temperature.

Items 4) and 5) are to be computed for the first and the fifth steps of VH1-HP and for the second step of VH1-HC.

(2) Whole Reactor Calculations

1) k_{eff} for the specified configurations and atom densities.

2) Reaction rate breakdown at the center of the core (center of the central graphite block in the radial cross section) in terms of fissions, captures and productions for each nuclide with normalization to a total absorption(fissions + captures) of unity, using the effective cross section obtained by the cell calculation.

3) The spectral indices ρ^{28}, δ^{25}, δ^{28} and C^* using neutron flux at the center of the core axis and effective cross section obtained by the cell calculation.

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5) ^{235}U and ^{238}U fission rate spatial distributions along the central axis of core and along the horizontal line on the axially mid-plane.

6) Temperature coefficient of reactivity between the initial and final steps of VH1-HP. In this calculation, the following definition should be used,

$$\alpha_T = \frac{1}{T_2 - T_1} \cdot \frac{k_{eff}(T_2) - k_{eff}(T_1)}{k_{eff}(T_2)\, k_{eff}(T_1)}$$

where α_T is a temperature coefficient of reactivity. T_1 , T_2 denote assembly temperatures.

7) Effective delayed neutron fraction and neutron generation time for two steps of VH1-HC.

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6. Experimental Results and Others

Experimental results of k_{eff} are shown in Table 12. Temperature coefficients of reactivity derived from the k_{eff} and temperature values in the Table 12, are given in Table 13. The values in these tables are modified from the raw data to meet the simplification for the benchmark. In Table 14 are given the constants which can be used in the benchmark calculation.

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Table 1 Dimensions of the assembly

Across flats	2400 mm
Axial length	2400 mm

Table 2 Dimensions of fuel block

Across flats	300 mm
Axial length	1200 mm
Fuel rod hole diameter	47.2 mm
Fuel rod hole pitch	65 mm

Table 3 Dimensions of graphite sheath and end cap

Graphite sheath	Outer diameter	46.8 mm
	Inner diameter	36.5 mm
	Length	732 mm
End cap	Diameter	36.6 mm
	Thickness	5 mm

Table 4 Dimensions and uranium content of fuel compact

Type			B-2	B-4
Kernel	Diameter		602 μm	599 μm
Coated particle	Coating	1st	79 μm	79 μm
		2nd	79 μm	78 μm
	Diameter		918 μm	913 μm
Fuel compact	Outer diameter		35.85 mm	35.98 mm
	Inner diameter		17.95 mm	17.96 mm
	Height		35.98 mm	36.01 mm
	Uranium content		20.999g	20.950g

Table 5 Uranium isotopic abundance

Isotope	Abundance (wt%)	
	B-2	B-4
^{234}U	0.0135	0.0321
^{235}U	2.000	4.000
^{236}U	0.0016	0.0252
^{238}U	97.985	95.943

Table 6 Atom densities in the fuel compact for cell calculation

Nuclide	Atom density [nuclei/(barn-cm)]	
	B-2	B-4
Fuel kernel		
^{234}U	3.1907E-6	7.5355E-6
^{235}U	4.7067E-4	9.3499E-4
^{236}U	3.7494E-7	5.8655E-6
^{238}U	2.2768E-2	2.2143E-2
^{16}O	4.6485E-2	4.6183E-2
^{10}B	1.8386E-8	1.8263E-8
^{11}B	7.4473E-8	7.3973E-8
1st coating layer		
^{12}C	5.97E-2	5.92E-2
^{10}B	2.19E-9	2.08E-9
^{11}B	8.51E-9	8.43E-9
2nd coating layer		
^{12}C	9.38E-2	9.38E-2
^{10}B	3.30E-9	3.30E-9
^{11}B	1.337E-8	1.337E-8

Nuclide	Atom density [nuclei/(barn-cm)]	
	B-2	B-4
1st and 2nd layers homogenized		
^{12}C	8.03E-2	8.000-2
^{10}B	2.82E-9	2.81E-9
^{11}B	1.14E-8	1.14E-8
Matrix graphite		
^{12}C	8.581E-2	8.481E-2
^{10}B	3.017E-9	2.982E-9
^{11}B	1.222E-8	1.208E-8
^{16}O	2.508E-6	2.599E-6
^{14}N	9.399E-6	9.741E-6

Table 7 Atom densities for homogenized fuel compact [cf. Fig. 8(b)]

Nuclide	Atom density [nuclei/(barn-cm)]	
	B-2	B-4
^{234}U	2.663E-7	6.250E-7
^{235}U	3.929E-5	7.755E-5
^{236}U	3.130E-8	4.865E-7
^{238}U	1.9002E-3	1.8369E-3
^{16}O	3.882E-3	3.832E-3
^{10}B	4.256E-9	4.218E-9
^{11}B	1.724E-8	1.708E-8
^{12}C	7.750E-2	7.675E-2
^{14}N	6.618E-6	6.858E-6

Central hole is not smeared.
One end cap is homogenized.

Table 8 Average number of coated particles in a fuel compact [cf. Fig. 8(b)]

Compact type	[Particles/Compact]
B-2 type	2.002E+4
B-4 type	2.0406E+4

Table 9 Atom densities for graphite [cf. Figs. 8(a), (b)]

Nuclide	Atom density [nuclei/(barn-cm)]	
	Graphite sheath and end cap	Graphite assembly
^{12}C	7.451E-2	8.356E-2
^{10}B	1.146E-9	1.285E-9
^{11}B	4.642E-9	5.206E-9
^{16}O	8.869E-6	8.837E-6
^{1}H	1.232E-5	1.225E-5

The atom densities are obtained from real material density of graphite diluting with volume of small clearances for rod or compact insertion and block pile-up.

Table 10 Assembly temperature and number of fuel rods in the core

Step	VH1-HP Temp. (℃)	VH1-HP Fuel rods B-4	VH1-HP Fuel rods B-2	VH1-HC Temp. (℃)	VH1-HC Fuel rods B-4	VH1-HC Fuel rods B-2
1	25.5	288	0	8.0	288	0
2	71.2	288	0	200.3	288	144
3	100.9	288	0			
4	150.5	288	0			
5	199.6	288	0			

The numbers of fuel rods given above are the sums of those in movable and fixed half assemblies

Table 11 Requested calculation items

Item	VH1-HP Step 1	2	3	4	5	VH1-HC 1	2
Cell calculation							
$k_\infty(0)$	x	x	x	x	x	x	x
B^2_{crit}, $k_\infty(B^2_{crit})$	x	x	x	x	x	x	x
M^2	x	x	x	x	x	x	x
Reaction rate	x				x		x
Spectral indices	x				x		x
Whole reactor calculation							
k_{eff}	x	x	x	x	x	x	x
Reaction rate	x				x		x
Spectral indices	x				x		x
Neutron balance	x				x	x	x
Fission distri.	x				x	x	x
Temperature coeft.	--------x--------						
β_{eff}						x	x
Λ (Generation time)						x	x

Table 12 Experimental k_{eff} values for various assembly temperatures

Step	VH1-HP		VH1-HC	
	Temp.(℃)	k_{eff}	Temp.(℃)	k_{eff}
1	25.5	1.008	8.0	1.010
2	71.2	1.001	200.3	0.998
3	100.9	0.996		
4	150.5	0.987		
5	199.6	0.979		

The k_{eff} values are corrected for loading irregularities and for the neglection of fuel rods in partially loaded blocks.

Table 13 Experimental values of temperature coefficients of reactivity for successive temperature ranges (VH1-HP)

Temp. range	Temperature coefficient of reactivity
(℃)	(10^{-4} $\Delta k/k/$℃)
25.5 to 71.2	-1.56
71.2 to 100.9	-1.79
100.9 to 150.5	-1.81
150.5 to 199.6	-1.77
25.5 to 199.6	-1.73

The coefficient values are excluded by the effects of,

1) fuel rods in partially loaded blocks
2) expansion of assembly and air in the assembly
3) assembly fixing steel frames.

Table 14 Constants for the benchmark

Mass number	1H	1.007825
	^{10}B	10.01294 (19.8 wt%)
	^{11}B	11.00931 (80.2 wt%)
	^{12}C	12.00000
	^{14}N	14.00307
	^{16}O	15.99492
	^{234}U	234.0409
	^{235}U	235.0439
	^{236}U	236.0456
	^{238}U	238.0508
Air contents	N_2	75.51 wt%
	O_2	23.01 wt%
Gas constant		8.31441 J/K/mol
Normal state		T=273.16 K
		P=1.01325x10 J/m
Avogadro's number		Av=6.022045E23

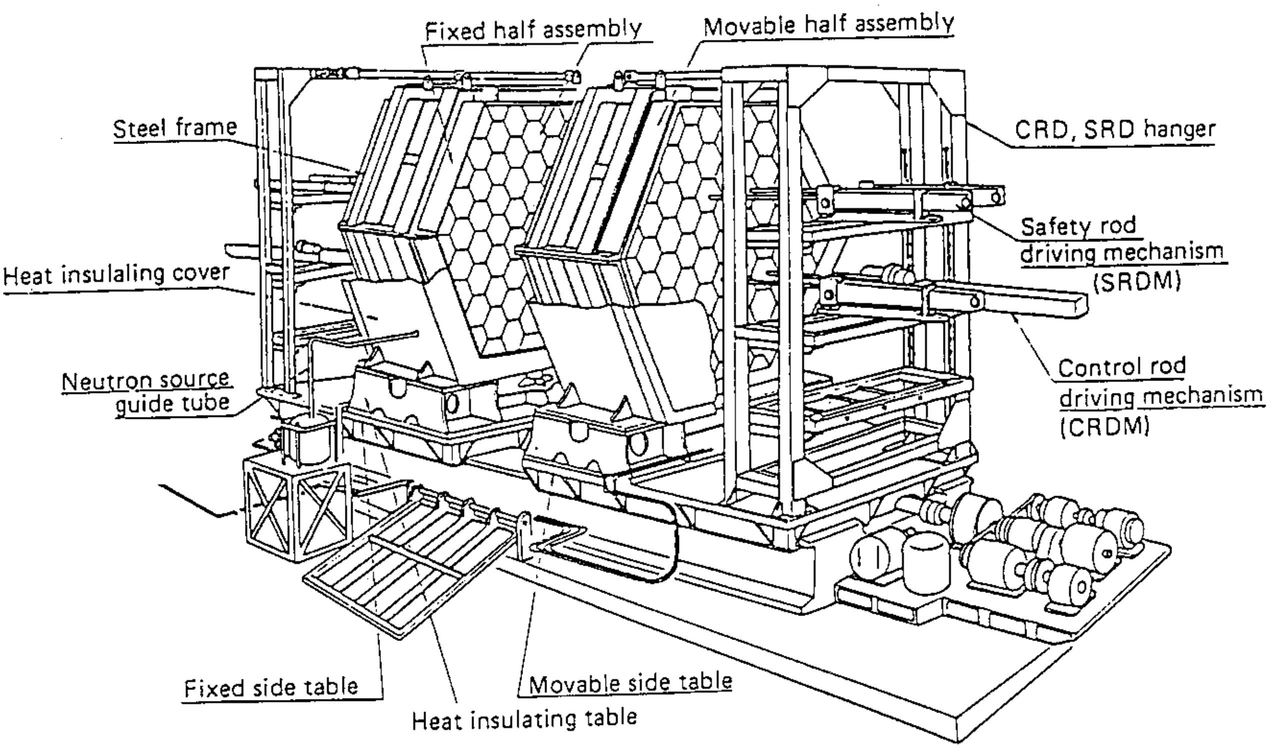
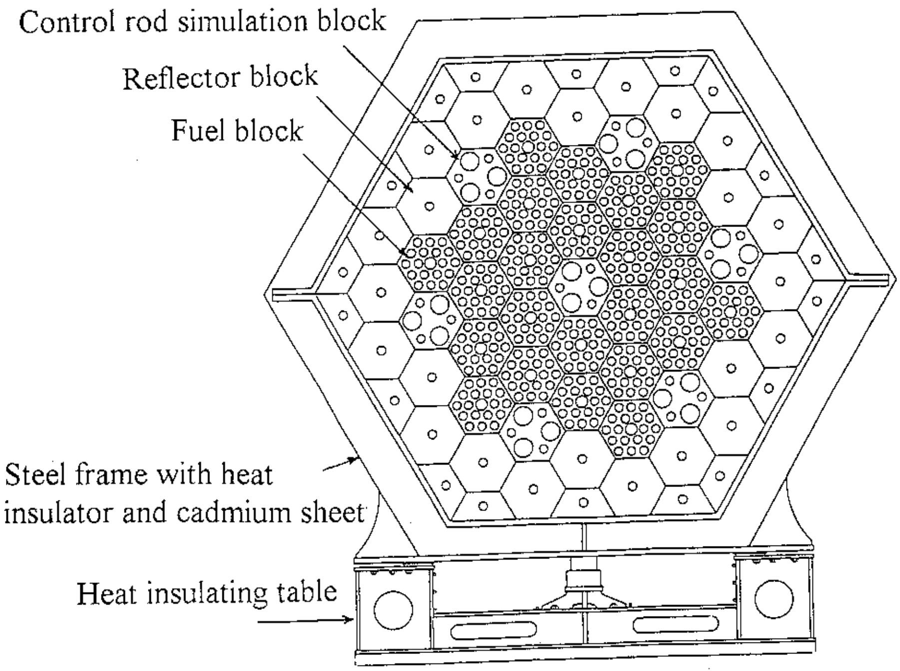


Fig. 1 Bird's eye view of the assembly



Circles in core and reflector indicate graphite rods. The rods in core can be replaced with fuel rods, while those in reflector can be replaced with heater rods.

Fig. 2 Cross section of the assembly

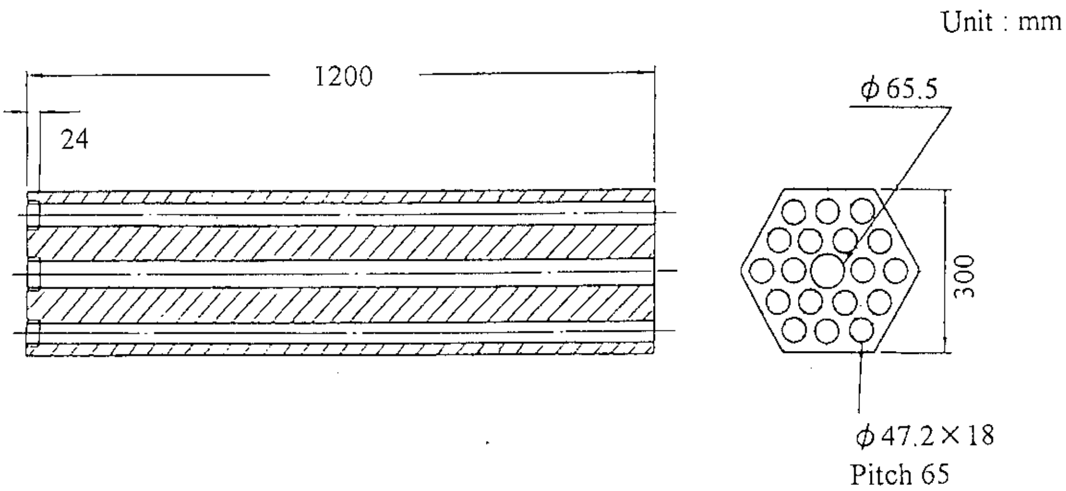
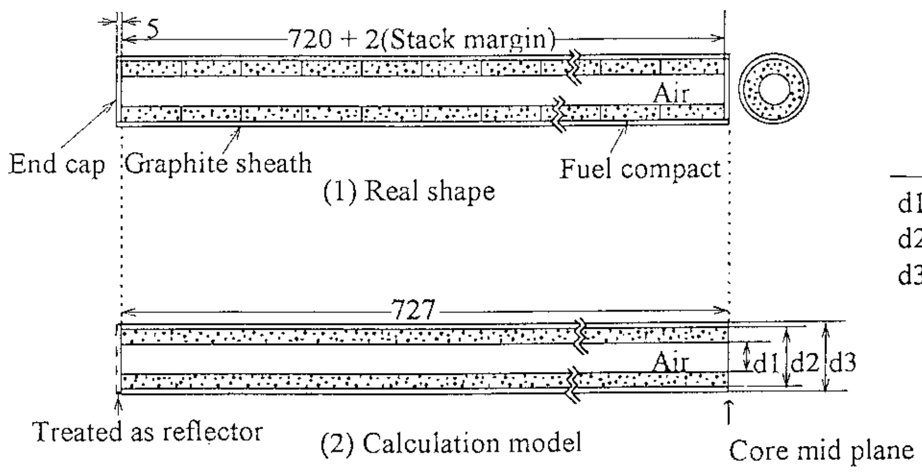


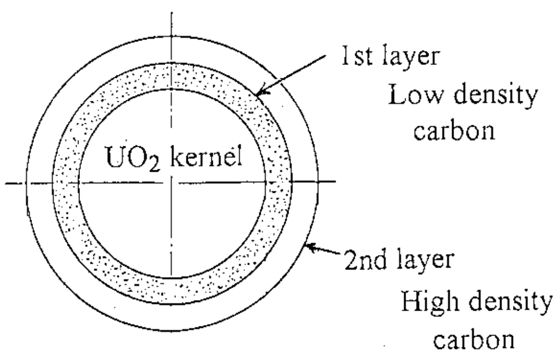
Fig. 3 Cross section of a graphite block



Unit : mm

	B-2	B-4
d1	17.95	17.96
d2	35.85	35.98
d3	47.20	47.20

Fig. 4 Cross section of a fuel rod and its calculation model



Diameters are given in Fig. 8(a).

Fig. 5 Cross section of a coated particle

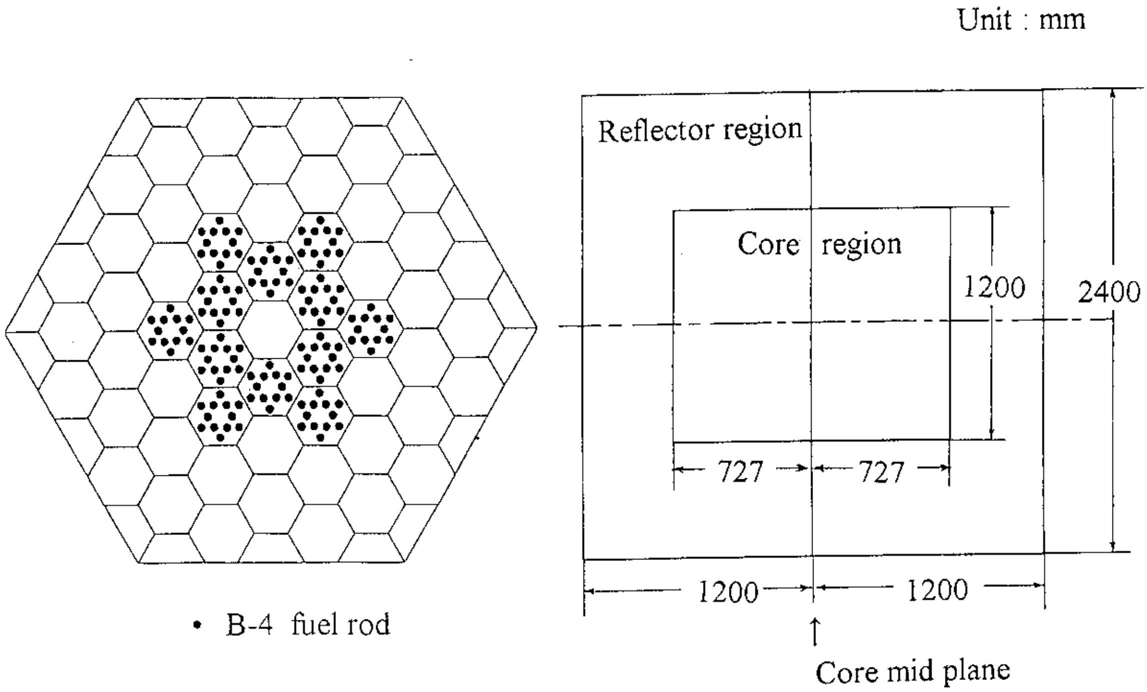


Fig. 6 Core loading pattern for VH1-HP and the first step of VH1-HC

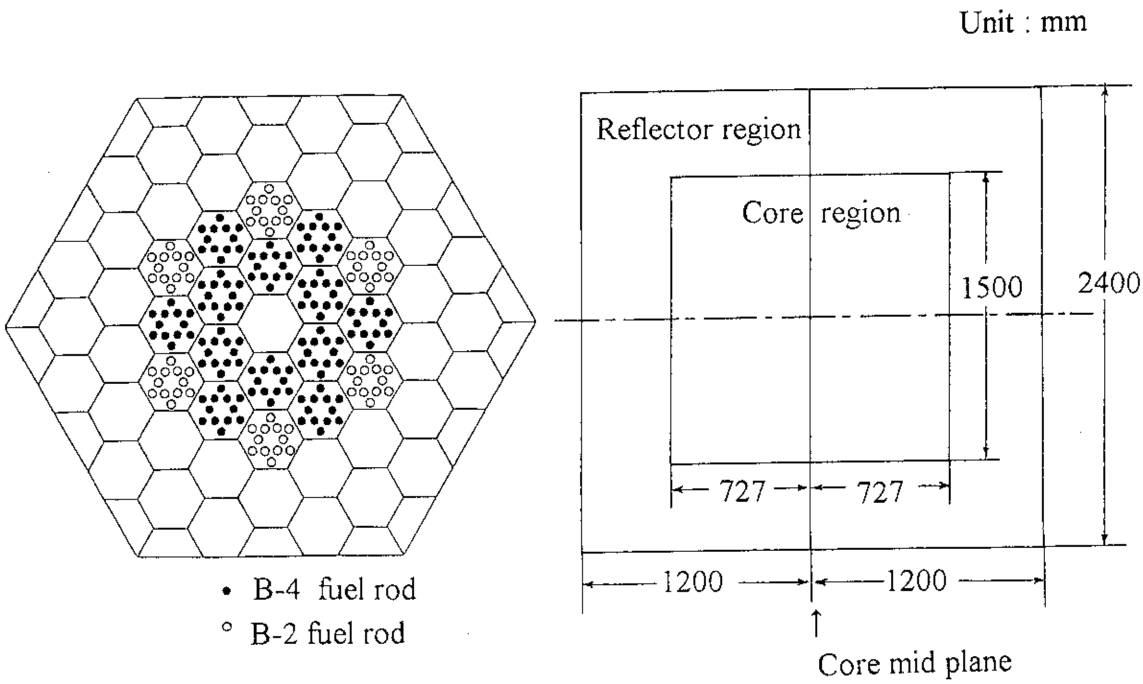
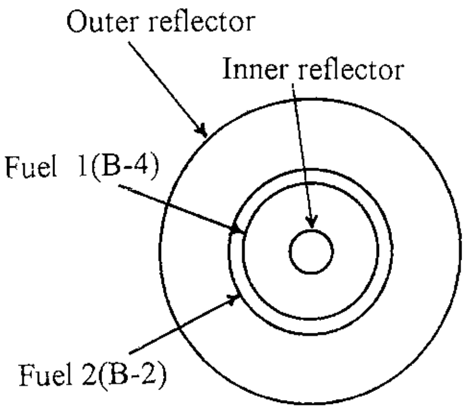


Fig. 7 Core loading pattern for the second step of VH1-HC

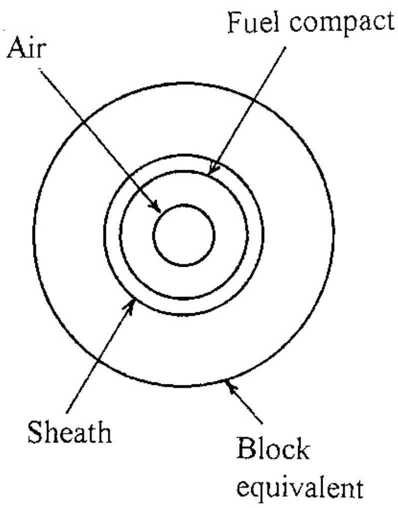
(a) Cylindrical reactor model

Region	Diameter(10^{-2} m)	
	VH1-HP	VH1-HC(200 ℃)
Inner reflector	31.50	31.50
Fuel 1(B-4)	113.58	113.58
Fuel 2(B-2)	-----	137.32
Outer reflector	252.02	252.02



(b) Macro cylindrical cell model
(Number 2 heterogeneity)

Region	Diameter(10^{-3} m)	
	B-2	B-4
Air	17.95	17.96
Fuel compact	35.85	35.98
Sheath	47.20	47.20
Block equivalent	90.94	90.94



(c) Micro sphere cell model
(Number 1 heterogeneity)

Region	Diameter(10^{-6} m)	
	B-2	B-4
Kernel	602	599
1st layer	760	757
2nd layer	918	913
Matrix equivalent	1374	1370

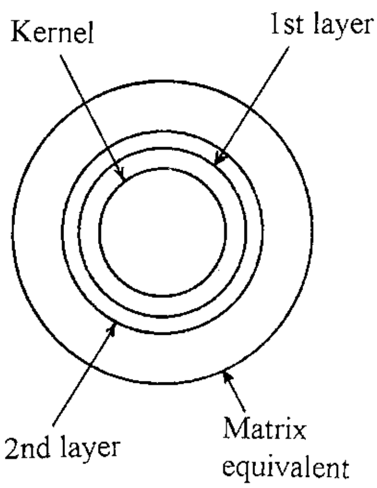


Fig. 8 Examples of calculation models

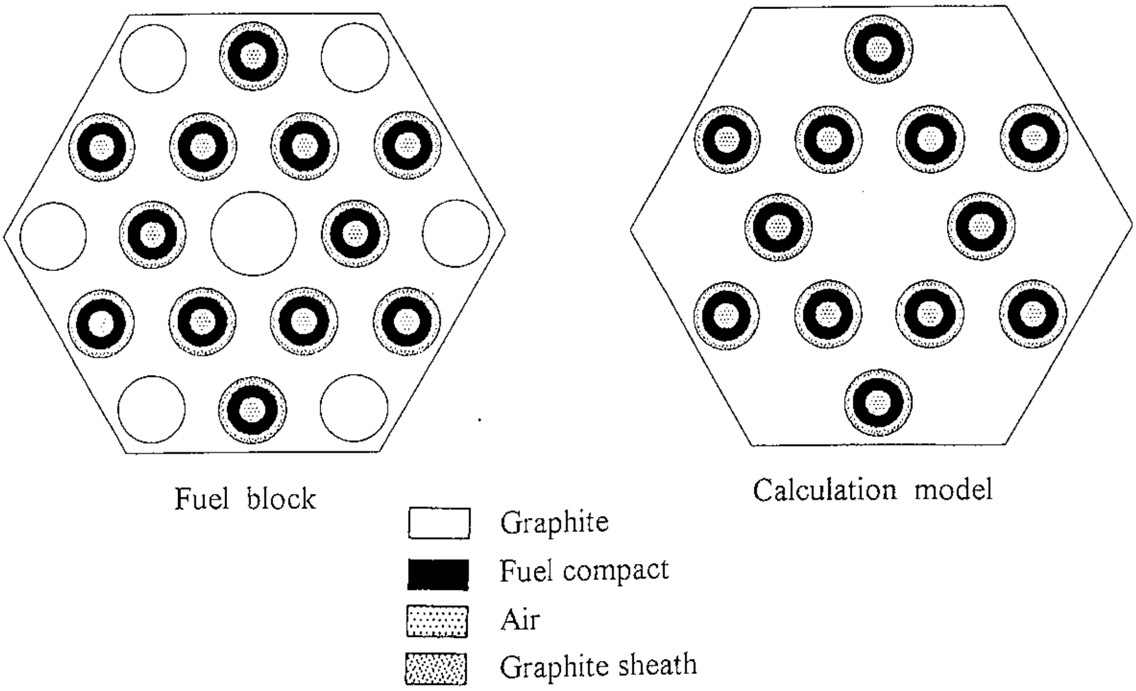


Fig. 9 Accurate cell calculation model

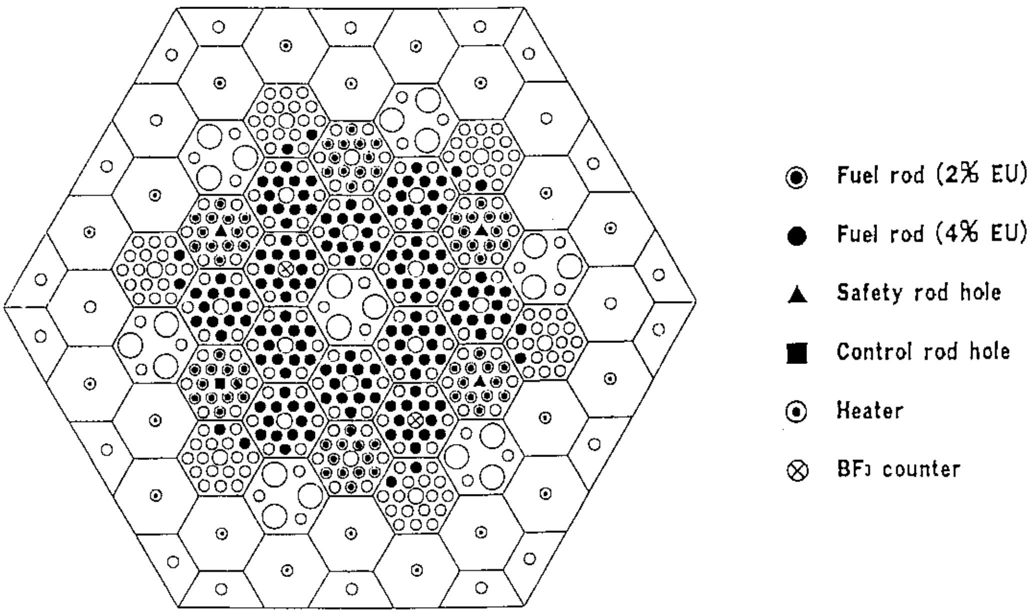


Fig. 10 Actual core loading for a core corresponding to the second step of VH1-HC