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COMPILATION REPORT OF VHTRC TEMPERATURE COEFFICIENT BENCHMARK CALCULATIONS

November 1995

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Compilation Report of
VHTRC Temperature Coefficient Benchmark Calculations

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A calculational benchmark problem has been proposed by JAERI to an IAEA Coordinated Research Program, 'Verification of Safety Related Neutronic Calculation for Low-enriched Gas-cooled Reactors' to investigate the accuracy of calculation results obtained by using codes of the participating countries. This benchmark is made on the basis of assembly heating experiments at a pin-in block type critical assembly, VHTRC. Requested calculation items are the cell parameters, effective multiplication factor, temperature coefficient of reactivity, reaction rates, fission rate distribution, etc. Seven institutions from five countries have joined the benchmark works. Calculation results are summarized in this report with some remarks by the authors. Each institute analyzed the problem by applying the calculation code system which was prepared for the HTGR development of individual country.

The nuclear data are mostly based on ENDF, however differ in the versions, B-Ⅲ, Ⅳ and V. Cell calculations were performed with variety of codes each considering double heterogeneity of the VHTRC fuel. Resonance absorptions were treated by multi-group neutron calculation.

Whole reactor calculations were performed by diffusion codes using different neutron energy group number approximations and also by a Monte Carlo code.

The values of the most important parameter, k_{eff}, by all institutes showed good agreement with each other and with the experimental ones within 1%. The temperature coefficient agreed within 13%. The values of several cell parameters calculated by several institutes did not agree with the other's ones. It will be necessary to check the calculation conditions again for getting better agreement. The δ^{28} values calculated by all institutes scattered considerably. Therefore, it remains yet to be investigated. Fission distributions were calculated. The results showed discrepancies due mainly to the different geometrical models in the whole reactor calculation.

Keywords: HTGR, Reactor Physics, Benchmark, Compilation, Low-enrich, VHTRC, Calculation, Effective Multiplication Factor, Temperature Coefficient, IAEA

VHTRC温度係数ベンチマーク計算結果編集報告書

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

（1995年10年18日受理）

本報告書はIAEA協力研究計画（低濃縮高温ガス炉の安全性に関する炉物理計算の精度検証）のもとに準備した高温ガス炉の炉物理ベンチマーク問題に対する各参加機関の計算結果を編集したものである。ベンチマーク問題は低濃縮ウラン被覆粒子燃料，黒鉛ブロック構造の臨界集合体VHTRCを常温から200度に昇温する場合の格子定数，増倍係数，反応度温度係数，反応率等を算出することを課題にしている。これまでに5ヵ国7機関が解析結果を提出しており，これらの結果を比較できるようにまとめて検討を加えた。研究機関ごとに自分達が開発，整備した計算システムを使って解析した。核データはENDFがほとんどだが研究機関ごとにバージョンは異なる。格子計算では燃料の2重非均質性を考慮している。共鳴吸収は多群扱いで計算している。炉心計算では拡散以外にモンテカルロ計算手法が使われた。最も重要なパラメータである実効増倍係数ではどの機関も実験値から1％の範囲内に収まった。反応度温度係数では13％以内で実験値と一致することが確かめられた。格子定数や核分裂率分布では計算モデルに依存して結果間にかなりの違いが見られるものもあった。特にδ^{28}などは不一致が顕著であり，今後の検討が必要である。核分裂率分布では炉心計算での幾何学的モデルの違い，エネルギー群数の違いが現れた。

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1. Introduction

The IAEA Coordinated Research Program (CRP) on "Validation of Safety Related Reactor Physics Calculations for Low-Enriched HTGRs", has been progressed using a pebble bed type critical assembly at the PROTEUS Facility of Paul Scherrer Institut in Villigen, Switzerland since April 1990. Prior to the experimental verification, a calculational benchmark problem was proposed by Mathews *et al* [1]. This problem however, did not include calculations of temperature dependence because there was not a proper experimental plan of this kind in the PROTEUS experiments. In order to compensate this point, a new benchmark problem was proposed at the second Research Coordination Meeting (RCM) of the CRP by Yasuda *et al* [2] on the basis of assembly heating experiments at a pin-in-block type critical assembly, VHTRC. Complete descriptions of this problem were separately published in a report [2].

This benchmark was intended to be useful for verifying:

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

(2) Calculation of effective multiplication factor

(3) Calculation of temperature coefficient in a low temperature range

The preliminary results of the benchmark have been reported at the third RCM by four institutes and a summary report [3] of them was presented by Yasuda at the fourth RCM. Until now, the following seven institutes have joined the benchmark.

* The Institute of Nuclear Energy Technology (INET) in China [4], [5]
* The KFA Research Center Jülich (KFA) in Germany [6],[7]
* The Japan Atomic Energy Research Institute (JAERI) in Japan [8]
* The Experimental Machine Building Design Bureau (OKBM) in Russia [9]
* The Kurchatov Institute (KI) in Russia [10]
* The General Atomics (GA) in the USA [11]
* The Oak Ridge National Laboratory in the USA [12]

This report is a compilation of the calculation results of these institutes as of the end of August 1995.

2. Benchmark Description

2.1 Benchmark Name and Type

Benchmark Name: (1) VH1-HP

: (2) VH1-HC

Type : (1) The VH1-HP asks to determine the temperature coefficient of reactivity for five temperature steps and other neutronic parameters.

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Benchmark Name: (1) VH1-HP

: (2) VH1-HC

Type : (1) The VH1-HP asks to determine the temperature coefficient of reactivity for five temperature steps and other neutronic parameters.

: (2) The VH1-HC asks to determine the effective multiplication factor of near-critical core at two temperatures and other neutronic parameters.

2.2 System Description

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 [13]. The outlook is shown in Fig. 1. Fuel rods are inserted in holes of the graphite blocks. Fuel compacts in a fuel rod are made of coated fuel particles uniformly dispersed in the graphite matrix.

In the experiments corresponding to the benchmark problem, the assembly was first brought to critical state at room temperature. The assembly was then heated stepwise by using electric heaters up to 200 °C. At each step, the assembly temperature was kept constant so that an isothermal condition was realized, and subcritical reactivity was measured by the pulsed neutron method. Descriptions of the experiment for this benchmark problem, VH1-HP, can be found in [14]. At 200 °C, criticality was again attained by fuel rod addition and control rod adjustment. Descriptions of the experiment for this VH1-HC benchmark can be found in [15].

2.3 Model Description

2.3.1 Assembly and Fuel Rod

The fuel loading pattern is simplified from the actual experimental pattern as shown in Fig. 2 for both all steps of the VH1-HP and the first step of VH1-HC, while for the second step of VH1-HC, is simplified as shown in Fig. 3. The shape of a fuel rod is modeled by a hollow cylinder. The experimental temperatures as well as the number of fuel rods in the core are summarized in Table 1.

2.3.2 Other Simplifications

The following simplifications were adopted for the ease of benchmark calculations .

(1) Temperature distribution can be treated as isothermal because it was sufficiently flat in the actual experiments.

(2) The thermal expansion of assembly should be neglected. The expansion effects were separately estimated and corrections are made to the experimental values.

(3) The loading irregularities, such as control rods, neutron detectors in the actual assembly can be also neglected. Those effects were independently measured or estimated numerically and corrections are made to the experimental values.

2.4 Unit Cell Result Definitions

The unit cell calculational results are requested for the following items.

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

2) The critical buckling $B^2{}_{crit}$ and k_∞ $(B^2{}_{crit})$, 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 (fission+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 cutoff 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,
δ^{28} = ratio of ^{238}U fissions to ^{235}U fissions(macroscopic),
C^* = ratio of ^{238}U captures to ^{235}U fissions(macroscopic).

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 fifth steps of the VH1-HP and for the second step of the VH1-HC.

2.5 Whole Reactor Result Definitions

The whole reactor calculation results are requested for the following items.

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

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 and 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^* at the center of the core.

4) Neutron balance in terms of absorption(unity), productions and leakage, integrated over the core region.

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 the VH1- HP. In this calculation, the following relation should be used.

$$a_T = \frac{1}{T_2 - T_1} \bullet \frac{k_{eff}(T_2) - k_{eff}(T_1)}{k_{eff}(T_2)\, k_{eff}(T_1)}$$

where a_T is 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.

Item 1) is to be computed for every step of temperature. Items 2) to 5) are to be computed for the first and fifth steps of the VH1-HP and for the second step of the VH1-HC.

3. Benchmark Results

3.1 Methods and Nuclear Data Used in Unit Cell Calculations

The INET calculations used the GAM/ZUT code for epithermal range, and THERMOS code for thermal range and the nuclear data was based mainly on the ENDF/B-IV. Buckling recycling technique was used to get accurate neutron spectra.

The KFA results were obtained by using the GAM and THERMOS codes in their stand-alone versions. The double heterogeneous resonance self-shielding was taken into account by a special method incorporated in ZUT-DGL. The cross sections were taken from a newly compiled GAM and THERMOS library on the basis of the ENDF/B-V and JEF-1 data files. The critical spectrum was obtained by the buckling recycling technique. Some cell calculations were also done using the AMPX-II code system, however, their results are not included in this compilation for simplicity.

The JAERI calculations used the SRAC code system. The cell calculation was performed with a collision probability module, PIJ. A right hexagonal graphite block with twelve fuel rods was chosen as a unit cell. Dominant resonance energy range was treated with the PEACO module. The cross section library was based on the ENDF/B-IV. Thermal scattering matrices were utilized from the ENDF/B-III. The core region cross sections were evaluated with the critically buckled core region neutron spectrum obtained in the cell calculation.

The OKBM results were obtained by using the NEKTAR and partly the WIMS-D4 taking account of double heterogeneity of the fuel. Epithermal parameters of the fuel cell were calculated with the NEKTAR. Space-energy distribution of thermal neutrons in the cell was calculated by using the THERMOS code. The used nuclear data library was the UKNDL for WIMS-D4 and a domestic file for NEKTAR.

The KI results were obtained by using the FLY code which could prepare multigroup constants from a domestic file by spherical or cylindrical unit cell calculations taking account of micro-particle structure. Iteration cycle was made between the CONSUL and the whole reactor calculation code, FLY, to get a suitable neutron spectrum.

The GA results were obtained by using MICROX code with GAM data for fast, GATHER data for thermal and GAR data for epithermal-resolved energy range neutrons, respectively. The ENDF/B-V nuclear data was used to calculate the cross sections. Simplification was introduced in the unit cell model, that is, the cell consisted of inner circular fuel zone and outer annular zone which was a mixture of graphite and air. Mean chord length was calculated for fuel compact and was used to determine the equivalent radius of the fuel zone.

The ORNL results were obtained by using a continuous energy Monte Carlo code, MCNP version 4.X using a very detailed model of the geometry of the configurations, taking account of micro-particles as well as graphite block structure. Calculations were done for an infinite two-dimensional hexagonal cell. It was assumed that the particles are arranged in a cubic lattice. Calculations were also done by a homogeneous model for comparisons. This result, however, are not included in this compilation. The nuclear data were based on the ENDF/B-V cross section library. The calculations corresponded only to a temperature, 300 K.

3.2 Methods Used in Whole Reactor Calculations

The INET results were obtained with the diffusion theory code, CITATION. Four neutron energy groups were used in two dimensional R-Z geometry.

The KFA results were obtained with the diffusion theory code, CITATION in the VSOP code system. Five neutron energy groups were used in two dimensional R-Z geometry.

The JAERI calculation results were obtained with the diffusion theory code, CITATION in the SRAC code system. Twenty-five energy groups were used in triangular-Z geometry.

The OKBM calculations were performed with the three dimensional diffusion theory code, JAR. Two group cross sections were used in the calculations.

The KI calculations were performed with the three dimensional diffusion theory code, CONSUL. Four group cross sections were used.

The GA results were obtained with the diffusion theory code, DIF3D by a triangular-Z geometry and nine energy groups for neutrons.

The ORNL calculations were performed with the MCNP. A three dimensional model was used to take account of the VHTRC hexagonal block structure accurately. The whole reactor calculation was performed considering particle-wise heterogeneity directly without the help of cell calculation.

Calculation methods and nuclear data used by each country are summarized in Table 2.

3.3 Calculation Results of VH1-HP Problem

3.3.1 Unit Cell Results

The unit cell calculation results of VH1-HP are summarized in Tables 3-5. Arithmetic average is also given for each quantity. The numbers in parentheses are the ratios of the calculated values to the arithmetic average for that quantity. The calculated values of unit cell parameters, $k_\infty(0)$, $B^2{}_{crit}$, $k_\infty(B^2{}_{crit})$ and M^2 are given in Table 3. Generally speaking, the values by OKBM deviate from those by the other institutes. A strong correlation is found between the magnitudes of $k_\infty(0)$ and $B^2{}_{crit}$ values. These values by OKBM are higher than those by the other institutes. Good agreements are seen for $k_\infty(B^2{}_{crit})$ at 25.5 °C among all institutes owing to a canceling effect of the two parameters. The $k_\infty(B^2{}_{crit})$ values by OKBM have a very weak temperature dependence. The M^2 values by KI are higher than those by others. Table 4 shows reaction rates. Reasonable agreement is observed for ^{235}U and ^{238}U, nevertheless, the values for ^{235}U and ^{238}U by INET are high and low, respectively. The ^{238}U

fission rates by ORNL are observed higher than the other institutes, in other words, the values by INET and KFA are lower than the other three institutes' values. On the other hand, considerable disagreements are found in the values for ^{234}U and ^{236}U in this table. Fortunately, these disagreements do not affect strongly on the k_{eff} value. In Table 5, are shown the spectral indices. The ρ^{28} values by INET are lower than those by the others.. The values δ^{25} agree well with each other except the very low OKBM values. On the other hand, the δ^{28} values by all institutes scatter considerably, especially those by JAERI and ORNL are high. The similar tendency has been pointed out in the LEUPRO-1 benchmark compilation by Mathews[16]. This fact may indicate that there are differences in fission cross sections for ^{238}U. The C^* values by all institutes show good agreement except OKBM values. The tendency of ORNL values can be understood by assuming a harder neutron spectrum. All values by KI are moderate.

3.3.2 Whole Reactor Results

The whole reactor calculation results of VH1-HP are summarized in Tables 6-10. The experimental values in the tables have been obtained from VHTRC heating experiments at subcritical states by using the pulsed neutron method. The numbers in parentheses are the ratios of the calculated values to the experimental one for that quantity. Effective multiplication factor, k_{eff}, of VH1-HP by the whole reactor calculation is given in Table 6, and its temperature dependence is shown in Fig. 4. The values of k_{eff} by all institutes showed good convergence within around 1 % except the OKBM results obtained using the NEKTAR/Domestic data file. The values by INET and KI show very excellent agreement with the experimental ones. All the values calculated by the other institutes are a little higher than the experimental one. This tendency will give generally a conservative estimate for criticality.

Temperature coefficient of reactivity for VH1-HP is listed in Table 7 and its temperature dependence is drawn in Fig. 5. Most plot points converge within -(1.5–2.0) x $10^{-4}\Delta k/k/°C$. The calculated results show weak temperature dependence in the analyzed temperature range, however, their tendencies cannot be commonly explained. It seems worthy to conduct experiments in a future at higher temperatures to evaluate extensively the results of this kind of calculations. In the lower temperature region, the experimental values show different behavior from the calculated ones. The assumption of proper change of humidity in graphite blocks and fuel compacts in the course of reactor temperature rise could not explain completely this phenomenon in the JAERI analysis.

Table 8 shows reaction rates for the whole reactor of VH1-HP. Values for ^{238}U by ORNL are higher than those by KFA and JAERI due to a different evaluation point in the core. Considerable disagreements are observed in the values for ^{234}U and ^{236}U. Spectral indices at the core center are given in Table 9. All values by ORNL are higher than those by JAERI and

KFA. The prominence of the ORNL results will be reflecting the choice of evaluation point in the core different from those of the other institutes, i.e., JAERI and KFA chose the central graphite block as the evaluation point, on the other hand, ORNL chose the fuel block adjacent to the central graphite block. There must be considerable difference in the neutron energy spectrum between the two blocks. JAERI and KFA gave similar values for ρ^{28}, δ^{25} and $C^{*}(macro)$, however, noticeable different values for $\delta^{28}(macro)$. The cause of this difference may be attributed to the difference in the data libraries. Core neutron balance for VH1-HP are shown in Table 10. The neutron production values are in good agreement between institutes for each temperature. The leakage is lower in the KFA results than in the JAERI and GA ones due to the difference of geometrical models.

Fission distributions for VH1-HP, 25.5 °C calculated using the effective cross sections of B-4 type cell are shown in Fig. 6. Each curve is simply normalized at the most left calculation point. The radial distributions have large discrepancies between institutes, especially for ^{238}U fissions. This fact will reflect the difference in the whole reactor geometrical models, i.e., the cylindrical(KFA), hexagonal(JAERI) and rigorous(ORNL) models. The axial distributions of ^{235}U (mainly thermal) fissions in Fig. 6(c) show discrepancies in the region, z >70 cm, i.e., in the axial reflector region. This will be caused mainly by the difference in the number of neutron energy groups. On the other hand, the ^{238}U (mainly fast) fission distributions in Fig. 6(d) show good agreement, although the ORNL results are scattering around the other institutes' curves due probably to statistical errors.

Fission distributions for VH1-HP, 199.6 °C calculated using the effective cross sections of B-4 type cell are shown in Fig. 7. Generally speaking, tendencies are similar to those in Fig. 6. Agreements are slightly better in Fig. 7(c) than in Fig. 6(c). This will be brought by the neutron spectrum hardening caused by the reactor temperature rise.

3.4 Calculation Results of VH1-HC Problem

3.4.1 Unit Cell Results

The unit cell calculation results of VH1-HC are summarized in Tables 11-13. Arithmetic average is also given for each quantity. The numbers in parentheses are the ratios of the calculated values to the arithmetic average for that quantity. The calculated values of unit cell parameters for the VH1-HC calculational benchmarks are given in Table 11. Agreements are fairly good between institutes for $k_\infty(0)$, $k_\infty(B^2_{crit})$ and M^2, while the relatively deficient agreement for B^2_{crit} suggests the necessity of further improvement in the calculation method and data. Table 12 shows reaction rates for the unit cell of VH1-HC. Reasonable agreement is observed in this table. The less important items such as reaction rates of ^{236}U, show the poorer agreements. In Table 13, the ρ^{28}, δ^{25} and C^{*} values show good convergence. On the other hand, the δ^{28} values by all institutes scatter considerably in the same way as that for

VH1-HP.

3.4.2 Whole Reactor Results

The whole reactor calculation results of VH1-HC are summarized in Tables 14-18. The numbers in parentheses are the ratios of the calculated values to the experimental one or the arithmetic average for that quantity. Effective multiplication factor for VH1-HC by the whole reactor calculation is given in Table 14. The experimental values in the table have been obtained from VHTRC heating experiments at critical states. In the experiment, fuel rods were added to the core at the elevated temperature to get the criticality condition again. Agreement is fairly good between institutes both for the two temperatures. All the calculated values are a little higher than the experimental ones similarly to Table 6.

Table 15 shows reaction rates at the core center of VH1-HC. Reasonable agreement is observed between institutes on the quantities in this table. The data on the B-4 column are very similar to those in Table 8. Spectral indices are given in Table 16. JAERI and KFA gave similar values for ρ^{28}, δ^{25} and $C^{*}(macro)$, however, noticeable different values for $\delta^{28}(macro)$. The cause of this difference may be attributed to the difference in the data libraries. Core neutron balance for VH1-HC is shown in Table 17 . The neutron production and leakage values are in satisfactory agreement between institutes for the two temperatures.

Fission distributions for VH1-HC, at 200.3 °C calculated by using the effective cross sections of B-2 type cell are shown in Fig. 8. The radial distributions have relatively large discrepancies here again between institutes due probably to the difference of whole core geometrical models. Fission distributions for VH1-HC, at 200.3 °C calculated using the effective cross sections of B-4 type cell are shown in Fig. 9 . The curves for B-4 type cell shown in each of (a)-(d) are very similar to those for B-2 type cell shown in Fig. 8. There is seen no observable difference between the two figures.

The calculation of effective delayed neutron fraction of ^{235}U fissions has been requested in the Benchmark Problem. JAERI only reported the calculated results as shown in Table 18.

4. Final Summary

A calculational benchmark problem has been proposed by JAERI to an IAEA Coordinated Research Program, 'Verification of Safety Related Neutronic Calculation for Low-enriched Gas-cooled Reactors' to investigate the accuracy of calculation results obtained by using codes of the participating countries. This benchmark is made on the basis of assembly heating experiments at a pin-in block type critical assembly, VHTRC. From a view point of HTGR neutronics, this problem has a complementary character with the LEU-HTR benchmark problem which is based on the experimental plan at a pebble bed type critical assembly of the

VH1-HP.

3.4.2 Whole Reactor Results

The whole reactor calculation results of VH1-HC are summarized in Tables 14-18. The numbers in parentheses are the ratios of the calculated values to the experimental one or the arithmetic average for that quantity. Effective multiplication factor for VH1-HC by the whole reactor calculation is given in Table 14. The experimental values in the table have been obtained from VHTRC heating experiments at critical states. In the experiment, fuel rods were added to the core at the elevated temperature to get the criticality condition again. Agreement is fairly good between institutes both for the two temperatures. All the calculated values are a little higher than the experimental ones similarly to Table 6.

Table 15 shows reaction rates at the core center of VH1-HC. Reasonable agreement is observed between institutes on the quantities in this table. The data on the B-4 column are very similar to those in Table 8. Spectral indices are given in Table 16. JAERI and KFA gave similar values for ρ^{28}, δ^{25} and $C^{*}(macro)$, however, noticeable different values for $\delta^{28}(macro)$. The cause of this difference may be attributed to the difference in the data libraries. Core neutron balance for VH1-HC is shown in Table 17. The neutron production and leakage values are in satisfactory agreement between institutes for the two temperatures.

Fission distributions for VH1-HC, at 200.3 °C calculated by using the effective cross sections of B-2 type cell are shown in Fig. 8. The radial distributions have relatively large discrepancies here again between institutes due probably to the difference of whole core geometrical models. Fission distributions for VH1-HC, at 200.3 °C calculated using the effective cross sections of B-4 type cell are shown in Fig. 9. The curves for B-4 type cell shown in each of (a)-(d) are very similar to those for B-2 type cell shown in Fig. 8. There is seen no observable difference between the two figures.

The calculation of effective delayed neutron fraction of ^{235}U fissions has been requested in the Benchmark Problem. JAERI only reported the calculated results as shown in Table 18.

4. Final Summary

A calculational benchmark problem has been proposed by JAERI to an IAEA Coordinated Research Program, 'Verification of Safety Related Neutronic Calculation for Low-enriched Gas-cooled Reactors' to investigate the accuracy of calculation results obtained by using codes of the participating countries. This benchmark is made on the basis of assembly heating experiments at a pin-in block type critical assembly, VHTRC. From a view point of HTGR neutronics, this problem has a complementary character with the LEU-HTR benchmark problem which is based on the experimental plan at a pebble bed type critical assembly of the

PROTEUS Facility. Seven institutions from five countries have joined the benchmark collaboration. Each institute analyzed the problem by applying the calculation code system which was prepared for the HTGR development of individual country. Calculation results as of the end of August 1995 are summarized in this report with some remarks by the authors.

The nuclear data are mostly based on ENDF, however differ in the versions, B-IV and V partly supplied from B-Ⅲ. Cell calculations were performed with variety of codes each considering double heterogeneity of the VHTRC fuel. There were differences in geometrical models, that is, some institutes used a cylindrical model and the other institutes used a model composed of a hexagon and cylinders. Attentions were paid on a point how to calculate the neutron spectrum considering the leakage, because the VHTRC is a small system compared with a power reactor. Resonance absorptions were treated by hyper-fine group neutron calculations.

Whole reactor calculations were performed by diffusion codes. Neutron energy groups were from 2(KI) to 25(JAERI). Besides, a Monte Carlo code was used for rigorous calculations, though, it introduced an approximation to particle arrangements.

Remarkable points in the calculation results are summarized below: The values of the most important parameter, k_{eff}, by all institutes showed good agreement with each other and with the experimental ones for both VH1-HP and VH1-HC. The values of several cell parameters calculated by some institutes did not agree well with those by others. It will be necessary to check the calculation conditions again for getting better agreement. The δ^{28} values calculated by all institutes scattered considerably. Therefore, it remains yet to be investigated. Fission distributions were calculated. The results showed discrepancies due mainly to the different geometrical models in the whole reactor calculation. The requested calculation item, β_{eff} was, so far, not calculated except by JAERI. The β_{eff}/Λ calculated by JAERI does not agree well with experimental value as reported in [17]. Therefore, this item should be investigated in the future for better understanding of HTGR neutronics.

Temperature coefficient benchmark was conducted to the extent of 200 °C. Continuation of temperature dependence benchmark to higher temperature range, to 1000 °C using the Russian critical assembly ASTRA, for example, will be helpful for further code verification.

Self-reflection was made on the definition and description of the benchmark problem. Due to uncertain descriptions, some institutes calculated different quantities from what the authors of the benchmark problem had intended. For instance, the volume integration should have been defined more clearly for reaction rate and fission rate distributions.

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Table 1 Assembly temperature and number of fuel rods in core

	VH1-HP			VH1-HC		
Step	Temp. (°C)	Fuel rods B-4	Fuel rods B-2	Temp. (°C)	Fuel rods B-4	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 number of fuel rods is the sum of those in movable and fixed half assemblies of VHTRC-1. The B-2 and B-4 indicate fuel rods of 2 and 4 wt% enriched ^{235}U, respectively.

Table 2 VHTRC benchmark calculation methods used by participating institutes

Institute	Nuclear data	Resonance calculation		Cell calculation			Whole reactor calculation		
		Code	Group	Code	Group	Geometry	Code	Group	Geometry
GA	ENDF / B-V	GAR	9k~15k	GAM GATHER MICROX	92 101 92+101	Coaxial cylinders	DIF3D	9	3D(T-Z)
INET	ENDF / B-IV	ZUT		GAM THERMOS		Cylinder	CITATION	4	2D(R-Z)
JAERI	ENDF / B-IV ENDF / B-III	PEACO	4.6k	[SRAC] PIJ	21+41	Hexagonal cylinder	[SRAC] CITATION	25	3D(T-Z)
KFA	ENDF / B-V JEF-1	ZUT-DGL		[VSOP] GAM THERMOS		Cylinder	[VSOP] CITATION	5	2D(R-Z)
KI	Domestic	Experiment correlated		FLY	26+77	Cylinder	CONSUL (Diffusion)	4	3D(T-Z)
OKBM	Domestic UKNDL	NEKTAR (plane)		WIMS-D4 THERMOS	67	Cylinder	JAR (Diffusion)	2	3D
ORNL	ENDF/B-V	[MCNP] V 4.X	Conti.	[MCNP] V 4.X	Cont.	Hexagonal cylinder	[MCNP] V 4.X	Cont.	3D(xyz)

Cont. : Continuous energy

Table 3 Unit cell results for VH1-HP : $k_\infty(0)$, B^2_{crit}

Temp. (°C)	25.5	71.2	100.9	150.5	199.6
$k_\infty(0)$					
GA	1.5071	1.5003	1.4962	1.4899	1.4843
	(0.993)	(0.994)	(0.993)	(0.993)	(0.990)
INET	1.5163	1.5115	1.5085	1.5035	1.4987
	(0.999)	(1.001)	(1.002)	(1.002)	(0.999)
JAERI	1.4945	1.4888	1.4852	1.4793	1.4736
	(0.985)	(0.986)	(0.986)	(0.986)	(0.983)
KFA	1.5031	1.4978	1.4944	1.4888	1.4834
	(0.990)	(0.992)	(0.992)	(0.992)	(0.989)
KI	1.4911	1.4840	1.4796	1.4725	1.4658
	(0.982)	(0.983)	(0.982)	(0.981)	(0.977)
OKBM	1.5820	1.5768	1.5735	1.5682	1.5633
	(1.042)	(1.044)	(1.045)	(1.045)	(1.042)
	1.5482*	-------	-------	-------	1.5291*
	(1.020)	(-------)	(-------)	(-------)	(1.020)
ORNL	1.5016	-------	-------	-------	-------
	(0.989)	(-------)	(-------)	(-------)	(-------)
Average	1.5180	1.5099	1.5062	1.5004	1.4997
B^2_{crit} [cm^{-2}]					
GA	0.8450E-3	0.8223E-3	0.8091E-3	0.7893E-3	0.7718E-3
	(1.002)	(0.989)	(0.986)	(0.983)	(0.983)
INET	0.848 E-3	0.828 E-3	0.817 E-3	0.799 E-3	0.782 E-3
	(1.005)	(0.996)	(0.995)	(0.995)	(0.996)
JAERI	0.8112E-3	0.7947E-3	0.7840E-3	0.7662E-3	0.7492E-3
	(0.962)	(0.956)	(0.955)	(0.954)	(0.954)
KFA	0.8304E-3	0.8126E-3	0.8015E-3	0.7838E-3	0.7675E-3
	(0.985)	(0.977)	(0.976)	(0.976)	(0.977)
KI	0.761E-3	0.742E-3	0.730E-3	0.710E-3	0.691E-3
	(0.902)	(0.892)	(0.889)	(0.884)	(0.880)
OKBM	1.025 E-3	0.99 E-3	0.984 E-3	0.971 E-3	0.95 E-3
	(1.215)	(1.190)	(1.199)	(1.209)	(1.210)
ORNL	0.7836E-3	-------	-------	-------	-------
	(0.929)	(-------)	(-------)	(-------)	(-------)
Average	0.8435E-3	0.8316E-3	0.8209E-3	0.8032E-3	0.7853E-3

1) Numbers in parentheses show ratios to the average.
2) OKBM values with * mark are calculated by using WIMS-D4/UKNDL.
3) KFA and ORNL results listed on the 25.5 °C column are calculated at 26.8 °C.

Table 3 (continued) Unit cell results for VH1-HP : $k_\infty(B^2{}_{crit})$, M^2

Temp. (°C)	25.5	71.2	100.9	150.5	199.6
$k_\infty(B^2{}_{crit})$					
GA	1.4550	1.4473	1.4427	1.4357	1.4294
	(1.001)	(0.999)	(0.997)	(0.996)	(0.995)
INET	1.4633	1.4600	1.4565	1.4508	1.4454
	(1.006)	(1.007)	(1.007)	(1.006)	(1.006)
JAERI	1.4436	1.4375	1.4336	1.4271	1.4210
	(0.993)	(0.992)	(0.991)	(0.990)	(0.989)
KFA	1.4515	1.4456	1.4418	1.4356	1.4298
	(0.998)	(0.997)	(0.997)	(0.996)	(0.996)
KI	1.4537	1.4450	1.4405	1.4327	1.4255
	(1.000)	(0.997)	(0.996)	(0.994)	(0.993)
OKBM	1.4686	1.4614	1.4642	1.4672	1.4659
	(1.010)	(1.008)	(1.012)	(1.018)	(1.021)
ORNL	1.4440	-------	-------	-------	-------
	(0.993)	(-------)	(-------)	(-------)	(-------)
Average	1.4542	1.4495	1.4466	1.4415	1.4362
M^2 [cm^2]					
GA	538.4	544.0	547.2	552.0	556.4
	(1.011)	(1.003)	(1.002)	(0.999)	(1.011)
INET	537.2	545.4	550.6	559.1	567.0
	(1.008)	(1.006)	(1.008)	(1.012)	(1.031)
JAERI	546.9	550.5	553.1	557.5	561.9
	(1.027)	(1.015)	(1.013)	(1.009)	(1.021)
KFA	543.8	548.3	551.2	555.8	559.9
	(1.021)	(1.011)	(1.009)	(1.006)	(1.018)
KI	596	600	603	609	616
	(1.119)	(1.106)	(1.104)	(1.102)	(1.120)
OKBM	457.2	466.1	471.8	481.4	490.5
	(0.858)	(0.859)	(0.864)	(0.871)	(0.891)
	475.3*	-------	-------	-------	499.8*
	(0.892)	(-------)	(-------)	(-------)	(0.908)
ORNL	566.6	-------	-------	-------	-------
	(1.064)	(-------)	(-------)	(-------)	(-------)
Average	532.7	542.4	546.2	552.5	550.2

1) Numbers in parentheses show ratios to the average.

2) OKBM values with * mark are calculated by using WIMS-D4/UKNDL.

3) KFA and ORNL results listed on the 25.5 °C column are calculated at 26.8 °C.

Table 4 Unit cell results for VH1-HP ; Reaction rate at $B^2=B^2_{crit}$

Temp (°C)	25.5			199.6		
	Capture	Fission	Production	Capture	Fission	Production
^{234}U						
GA	1.551E-3	1.167E-5	2.924E-5	1.535E-3	1.152E-5	2.887E-5
INET	------	------	------	------	------	------
JAERI	1.420E-3	7.022E-6	1.827E-5	1.405E-3	6.953E-6	1.809E-5
KFA	1.575E-3	6.624E-6	1.691E-5	1.565E-3	6.564E-6	1.675E-5
ORNL	1.261E-3	2.048E-5	------	------	------	------
^{235}U						
GA	0.1158	0.5926	1.444	0.1155	0.5821	1.419
INET	0.1226	0.6001	------	0.1224	0.5919	------
JAERI	0.1154	0.5919	1.432	0.1154	0.5826	1.409
KFA	0.1171	0.5923	1.443	0.1170	0.5834	1.422
ORNL	0.1145	0.5882	------	------	------	------
^{236}U						
GA	3.433E-4	6.512E-6	1.579E-5	3.410E-4	6.455E-6	1.565E-5
INET	------	------	------	------	------	------
JAERI	3.344E-4	2.293E-6	6.183E-6	3.320E-4	2.270E-6	6.120E-6
KFA	3.545E-4	5.812E-6	1.397E-5	3.530E-4	5.772E-6	1.387E-5
ORNL	3.037E-4	3.887E-6	------	------	------	------
^{238}U						
GA	0.2467	0.003913	0.01083	0.2577	0.003861	0.01068
INET	0.2348	0.002560	------	0.2434	0.002536	------
JAERI	0.2471	0.004217	0.01161	0.2568	0.004174	0.01149
KFA	0.2421	0.002982	0.00814	0.2514	0.002951	0.00806
ORNL	0.2518	0.004226	------	------	------	------

KFA and ORNL results listed on the 25.5 °C column are calculated at 26.8 °C.

Table 5 Unit cell results for VH1-HP : Spectral indices

Temp.(°C)	25.5	199.6	Temp.(°C)	25.5	199.6
ρ^{28}			δ^{28} *(macro)*		
GA	2.776	2.932	GA	6.604E-3	6.633E-3
	(1.013)	(1.034)		(1.135)	(1.173)
INET	2.481	2.578	INET	4.266E-3	4.285E-3
	(0.905)	(0.909)		(0.733)	(0.758)
JAERI	2.825	2.956	JAERI	7.125E-3	7.164E-3
	(1.031)	(1.042)		(1.225)	(1.267)
KFA	2.736	2.869	KFA	5.035E-3	5.059E-3
	(0.998)	(1.012)		(0.866)	(0.895)
KI	2.628	2.735	KI	6.051E-3	6.114E-3
	(0.959)	(0.964)		(1.040)	(1.082)
OKBM	2.756	2.947	OKBM	4.571E-3	4.663E-3
	(1.006)	(1.039)		(0.786)	(0.825)
ORNL	2.980	------	ORNL	7.061E-3	------
	(1.087)	(------)		(1.214)	(------)
Average	2.740	2.836	Average	5.816E-3	5.653E-3
δ^{25}			C *(macro)*		
GA	7.232E-2	7.365E-2	GA	0.4164	0.4427
	(1.001)	(1.016)		(1.034)	(1.053)
INET	7.016E-2	7.100E-2	INET	0.3912	0.4113
	(0.971)	(0.979)		(0.972)	(0.978)
JAERI	7.464E-2	7.560E-2	JAERI	0.4175	0.4407
	(1.033)	(1.042)		(1.037)	(1.048)
KFA	7.804E-2	7.933E-2	KFA	0.409	0.431
	(1.080)	(1.094)		(1.016)	(1.025)
KI	7.276E-2	7.372E-2	KI	0.3959	0.4242
	(1.007)	(1.017)		(0.984)	(1.009)
OKBM	6.087E-2	6.183E-2	OKBM	0.352	0.373
	(0.842)	(0.853)		(0.875)	(0.887)
ORNL	7.698E-2	------	ORNL	0.4356	------
	(1.065)	(------)		(1.082)	(------)
Average	7.225E-2	7.252E-2	Average	0.4025	0.4205

1) Numbers in parentheses show ratios to the average.

2) KFA and ORNL results listed on the 25.5 °C column are calculated at 26.8 °C.

Table 6 Whole reactor results for VH1-HP : Effective multiplication factor

Temp.(°C)	25.5	71.2	100.9	150.5	199.6
Expt.	1.008	1.001	0.996	0.987	0.979
Calc.					
GA	1.0134	1.0044	0.9987	0.9897	0.9816
	(1.005)	(1.003)	(1.003)	(1.003)	(1.003)
INET	1.0107	1.0024	0.9972	0.9888	0.9808
	(1.003)	(1.001)	(1.001)	(1.002)	(1.002)
JAERI	1.0161	1.0085	1.0033	0.9946	0.9861
	(1.008)	(1.007)	(1.007)	(1.008)	(1.007)
KFA	1.0164	1.0095	1.0050	0.9975	0.9902
	(1.008)	(1.008)	(1.009)	(1.011)	(1.011)
KI	1.0095	1.0016	0.9966	0.9884	0.9808
	(1.001)	(1.001)	(1.001)	(1.001)	(1.002)
OKBM	1.0391	1.0292	1.0229	1.0129	1.0036
	(1.031)	(1.028)	(1.027)	(1.026)	(1.025)
	1.0165*	1.0085*	1.0037*	0.9958*	0.9887*
	(1.008)	(1.007)	(1.008)	(1.009)	(1.010)
ORNL	1.0113	------	------	------	------
	(1.003)	(------)	(------)	(------)	(------)

1) OKBM values with * mark are calculated by using macroscopic cross sections obtained by WIMS-D4/UKNDL.
2) Numbers in parentheses show C/E ratios.
3) KFA and ORNL results listed on the 25.5 °C column are calculated at 26.8 °C.

Table 7 Whole reactor results for VH1-HP : Temperature coefficient [$10^{-4}\Delta k/k/°C$]

Temp. range (°C)	25.5-71.2	71.2-100.9	100.9-150.5	150.5-199.6	25.5-199.6
Expt.	-1.56	-1.79	-1.81	-1.77	-1.73
Calc.					
GA	-1.935	-1.931	-1.836	-1.698	-1.836
	(1.240)	(1.069)	(1.014)	(0.959)	(1.061)
INET	-1.79	-1.75	-1.73	-1.67	-1.73
	(1.147)	(0.978)	(0.956)	(0.944)	(1.000)
JAERI	-1.64	-1.72	-1.75	-1.77	-1.72
	(1.049)	(0.936)	(0.969)	(1.000)	(0.995)
KFA	-1.52	-1.49	-1.51	-1.51	-1.51
	(0.974)	(0.832)	(0.834)	(0.853)	(0.873)
KI	-1.71	-1.70	-1.67	-1.61	-1.67
	(1.096)	(0.950)	(0.923)	(0.910)	(0.965)
OKBM	-2.03	-2.01	-1.94	-1.86	-1.95
	(1.301)	(1.123)	(1.072)	(1.051)	(1.127)
	-1.71*	-1.61*	-1.59*	-1.47*	-1.60*
	(1.096)	(0.899)	(0.878)	(0.831)	(0.925)

1) Numbers in parentheses show C/E ratios.

2) The OKBM values with * mark are calculated by using macroscopic cross sections obtained by WIMS-D4/UKNDL.

3) KFA results listed on the lines 25.5-71.2 °C and 25.5-199.6 °C are given in the ranges 26.8-71.2 °C and 26.8-199.0 °C, respectively.

Table 8 Whole reactor results for VH1-HP ; Reaction rate at core center

Temp (°C)	25.5			199.6		
	Capture	Fission	Production	Capture	Fission	Production
^{234}U						
JAERI	1.268E-3	2.108E-6	5.455E-6	1.278E-3	2.233E-6	5.779E-6
KFA	1.410E-3	6.197E-6	1.495E-5	1.419E-3	6.226E-6	1.504E-5
ORNL	2.847E-3	8.410E-6	------	------	------	------
^{235}U						
JAERI	0.1205	0.6584	1.593	0.1207	0.6455	1.561
KFA	0.1213	0.6535	1.592	0.1217	0.6426	1.566
ORNL	0.1189	0.6200	------	------	------	------
^{236}U						
JAERI	2.191E-4	6.642E-7	1.781E-6	2.298E-4	7.037E-7	1.886E-6
KFA	2.368E-4	3.327E-6	7.850E-6	2.458E-4	3.463E-6	8.172E-6
ORNL	1.126E-4	9.701E-7	------	------	------	------
^{238}U						
JAERI	0.1765	0.001188	0.003250	0.1893	0.001259	0.003443
KFA	0.1756	0.000846	0.002310	0.1864	0.000884	0.002415
ORNL	0.2116	0.003504	------	------	------	------

1) A special slab was defined for reaction rate calculation in the ORNL analysis.

2) KFA and ORNL results listed on the 25.5 °C column are calculated at 26.8 °C.

Table 9 Whole reactor results for VH1-HP : Spectral indices at core center

Temp.(°C)	25.5	199.6	Temp.(°C)	25.5	199.6
ρ^{28}			$\delta^{28}(macro)$		
JAERI	1.410	1.575	JAERI	1.804E-3	1.950E-3
	(0.873)	(1.016)		(0.602)	(1.173)
KFA	1.383	1.525	KFA	1.294E-3	1.376E-3
	(0.856)	(0.984)		(0.432)	(0.827)
ORNL	2.054	------	ORNL	5.886E-3	------
	(1.271)	(------)		(1.965)	(------)
Average	1.616	1.550	Average	2.995E-3	1.663E-3
δ^{25}			$C^*(macro)$		
JAERI	3.704E-2	4.042E-2	JAERI	0.2681	0.2933
	(0.837)	(0.974)		(0.919)	(1.005)
KFA	3.975E-2	4.262E-2	KFA	0.2687	0.2902
	(0.898)	(1.026)		(0.921)	(0.995)
ORNL	5.594E-2	------	ORNL	0.3383	------
	(1.264)	(------)		(1.160)	(------)
Average	4.424E-2	4.152E-2	Average	0.2917	0.2918

1) Numbers in parentheses show ratios to the average.

2) JAERI results are given at the center of the assembly, i.e., r=5cm, z=4.37cm (mesh center) in T-Z model. On the other hand, the ORNL results are given at the column adjacent to the central graphite block. Slab thickness is 10cm (0.5 to 10.5cm from mid plane).

3) KFA and ORNL results listed on the 25.5 °C column are calculated at 26.8 °C.

Table 10 Whole reactor results for VH1-HP : Core neutron balance

Temp.(°C)	25.5	199.6	Temp.(°C)	25.5	199.6
Production			*Leakage*		
GA	1.539	1.561	GA	0.539	0.561
	(1.007)	(1.007)		(1.019)	(1.021)
JAERI	1.528	1.550	JAERI	0.528	0.550
	(0.999)	(1.000)		(0.998)	(1.001)
KFA	1.5197	1.5379	KFA	0.5197	0.5379
	(0.994)	(0.992)		(0.983)	(0.979)
Average	1.529	1.550	Average	0.529	0.550

1) Numbers in parentheses show ratios to the average.

2) KFA results listed on the 25.5 °C column are calculated at 26.8 °C.

Table 11 Unit cell results for VH1-HC : $k_\infty(0)$, $B^2{}_{crit}$, $k_\infty(B^2{}_{crit})$, M^2

Temperature (°C)	8.0	200.3	200.3
Cell	B4-cell	B4-cell	B2-cell
$k_\infty(0)$			
GA	1.5097	1.4846	1.3146
	(1.004)	(1.003)	(1.004)
JAERI	1.4966	1.4735	1.3046
	(0.996)	(0.995)	(0.997)
KFA	1.5031	1.4833	1.3071
	(------)	(1.002)	(0.999)
Average	1.5032	1.4805	1.309
$B^2{}_{crit}$ [cm^{-2}]			
GA	8.538E-4	7.716E-4	4.210E-4
	(1.022)	(1.012)	(1.022)
JAERI	8.174E-4	7.490E-4	4.055E-4
	(0.978)	(0.982)	(0.984)
KFA	8.304E-4	7.672E-4	4.096E-4
	(------)	(1.006)	(0.994)
Average	8.356E-4	7.626E-4	4.120E-4
$k_\infty(B^2{}_{crit})$			
GA	1.4580	1.4293	1.2752
	(1.004)	(1.002)	(0.999)
JAERI	1.4460	1.4209	1.2670
	(0.996)	(0.996)	(0.997)
KFA	1.4515	1.4297	1.2698
	(------)	(1.002)	(0.999)
Average	1.452	1.427	1.271
M^2 [cm^2]			
GA	536.3	556.4	653.7
	(0.991)	(0.995)	(0.995)
JAERI	545.6	561.9	658.6
	(1.009)	(1.004)	(1.002)
KFA	543.8	560.1	658.7
	(------)	(1.001)	(1.003)
Average	541.0	559.5	657.0

1) Numbers in parentheses show ratio to the average.
2) KFA results listed on the 8.0 °C column are calculated at 26.8 °C. They are not included in taking an average.

Table 12 Unit cell results for VH1-HC ; Reaction rates at 200.3 °C

	B-2			B-4		
	Capture	Fission	Production	Capture	Fission	Production
^{234}U						
GA	9.294E-4	5.854E-6	1.445E-5	1.535E-3	1.152E-5	2.887E-5
JAERI	8.530E-4	2.709E-6	7.045E-6	1.405E-3	6.953E-6	1.810E-5
KFA	6.283E-4	2.561E-6	6.531E-6	1.565E-3	6.564E-6	1.675E-5
^{235}U						
GA	0.09720	0.5191	1.265	0.1155	0.5821	1.419
JAERI	0.09719	0.5193	1.256	0.1154	0.5826	1.410
KFA	0.09778	0.5186	1.263	0.1170	0.5834	1.422
^{236}U						
GA	2.345E-5	4.143E-7	1.000E-6	3.410E-4	6.455E-6	1.565E-5
JAERI	2.290E-5	1.333E-7	3.593E-7	3.320E-4	2.270E-6	6.123E-6
KFA	2.416E-5	3.574E-7	8.572E-7	3.530E-4	5.772E-6	1.387E-5
^{238}U						
GA	0.3133	0.003605	0.00997	0.2577	0.003861	0.01068
JAERI	0.3127	0.003936	0.01083	0.2568	0.004174	0.01150
KFA	0.3066	0.002766	0.00756	0.2515	0.002951	0.00806

Table 13 Unit cell results for VH1-HC : Spectral indices at 200.3 °C

	B-2	B-4		B-2	B-4
ρ^{28}			δ^{28} (*macro*)		
GA	1.567	2.932	GA	6.945E-3	6.633E-3
JAERI	1.588	2.956	JAERI	7.578E-3	7.164E-3
KFA	1.532	2.870	KFA	5.334E-3	5.060E-3
δ^{25}			C^*(*macro*)		
GA	4.000E-2	7.365E-2	GA	6.034E-1	4.428E-1
JAERI	4.101E-2	7.561E-2	JAERI	6.021E-1	4.408E-1
KFA	4.280E-2	7.934E-2	KFA	5.91E-1	4.31E-1

Table 14 Whole reactor results for VH1-HC
: Effective multiplication factor

Temp.(°C)	8.0	200.3
Expt.	1.010	0.998
Calc.		
GA	1.0168	0.9986
	(1.007)	(1.001)
INET	1.0113	1.0027
	(1.001)	(1.005)
JAERI	1.0190	1.0009
	(1.009)	(1.003)
KFA	1.0164	1.0073
	(-----)	(1.009)
KI	1.0128	1.0148
	(1.003)	(1.017)

1) Numbers in parentheses show C/E ratios.
2) The experimental k_{eff} values are corrected for loading irregularities and for the neglect of fuel rods in partially loaded blocks in the experiment.
3) KFA result listed on the 8.0 °C column is calculated at 26.8 °C.

Table 15 Whole reactor results for VH1-HC ; Reaction rates at 200.3 °C core center

	B-2			B-4		
	Capture	Fission	Production	Capture	Fission	Production
^{234}U						
JAERI	8.700E-4	1.461E-6	3.781E-6	1.279E-3	2.198E-6	5.686E-6
KFA	9.592E-4	4.172E-6	1.006E-5	1.418E-3	6.184E-6	1.492E-5
^{235}U						
JAERI	0.09822	0.5261	1.273	0.1208	0.6456	1.562
KFA	0.09891	0.5271	1.284	0.1218	0.6429	1.567
^{236}U						
JAERI	2.331E-5	6.948E-8	1.863E-7	2.300E-4	6.923E-7	1.855E-6
KFA	2.432E-5	3.397E-7	8.010E-7	2.451E-4	3.439E-6	8.113E-6
^{238}U						
JAERI	0.3072	0.001977	0.005465	0.1892	0.001237	0.003385
KFA	0.2976	0.001327	0.003623	0.1860	0.000858	0.002343

Table 16 Whole reactor results for VH1-HC : Spectral indices at 200.3 °C core center

	B-2	B-4		B-2	B-4
ρ^{28}			δ^{28} *(macro)*		
JAERI	1.511	1.572	JAERI	3.796E-3	1.916E-3
KFA	1.414	1.515	KFA	2.518E-3	1.335E-3
δ^{25}			C^**(macro)*		
JAERI	3.942E-2	4.040E-2	JAERI	5.840E-1	2.931E-1
KFA	3.990E-2	4.245E-2	KFA	5.646E-1	2.893E-1

Table 17 Whole reactor results for VH1-HC : Core neutron balance

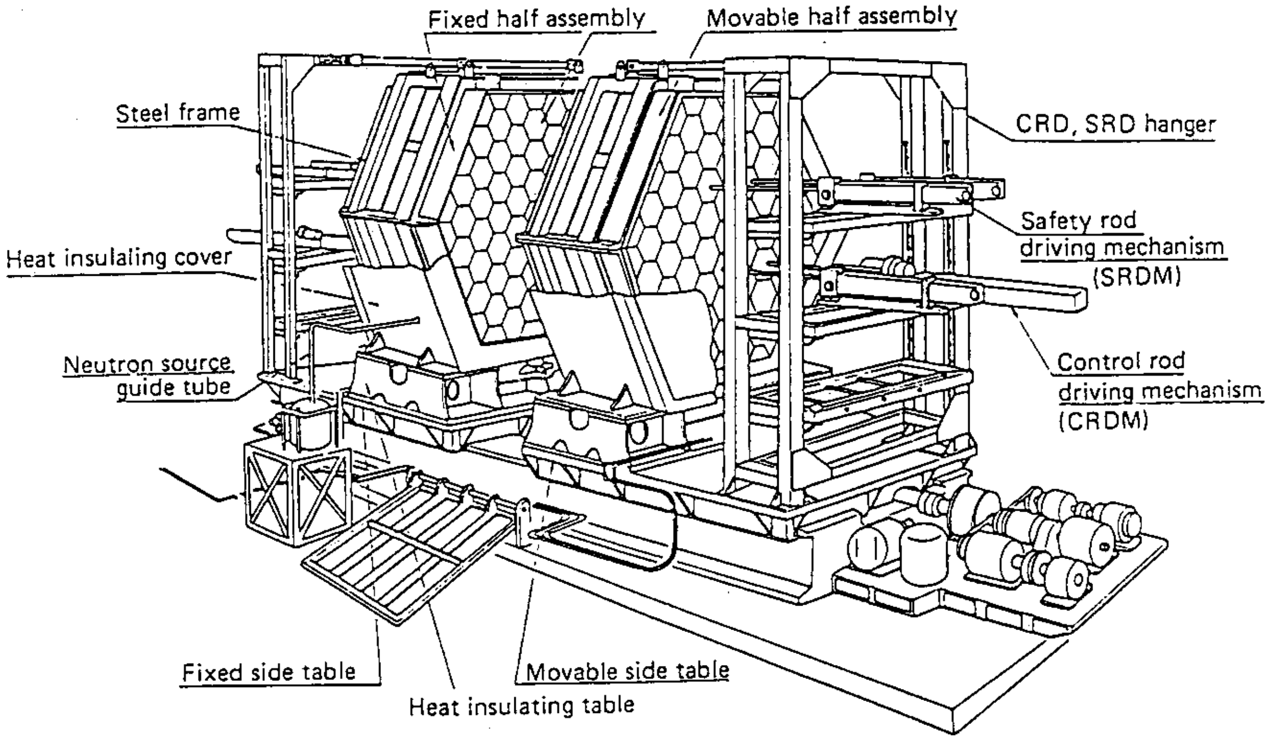
Temp.(°C)	8.0	200.3	Temp.(°C)	8.0	200.3
Production			*Leakage*		
GA	1.537	1.465	GA	0.537	0.465
	(1.004)	(1.006)		(1.010)	(1.019)
JAERI	1.526	1.455	JAERI	0.526	0.455
	(0.996)	(0.999)		(0.990)	(0.997)
KFA	1.5197	1.4492	KFA	0.5197	0.4492
	(------)	(0.995)		(------)	(0.984)
Average	1.532	1.456	Average	0.532	0.456

1) Numbers in parentheses show ratios to the average.

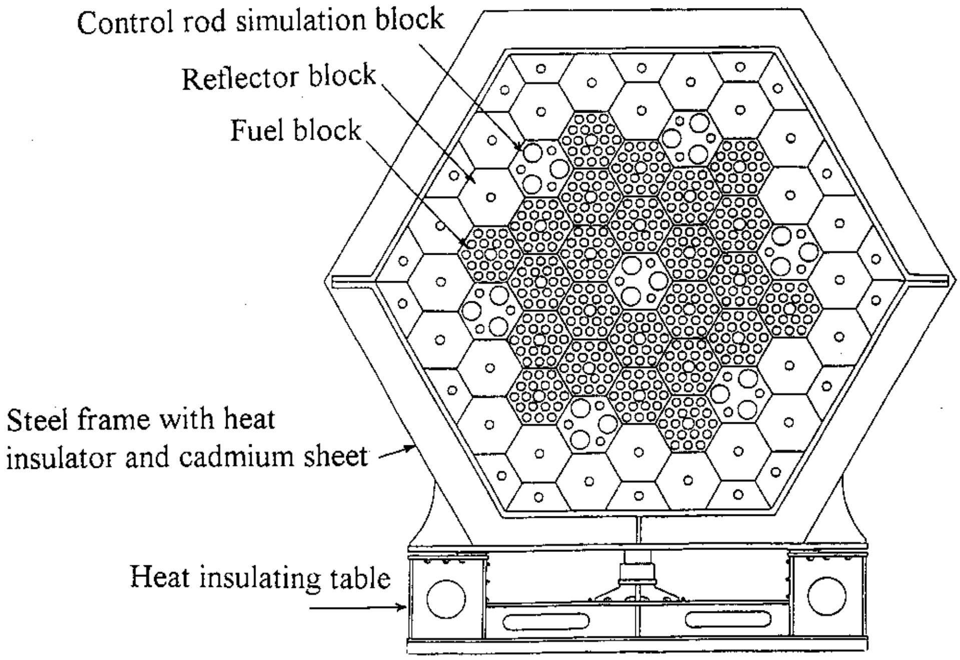
2) KFA results listed on the 8.0 °C column are calculated at 26.8 °C. They are not included in taking an average.

Table 18 Whole reactor results for VH1-HC
: Effective delayed neutron fraction

Temp.(°C)	8.0	200.3
β_{eff}		
JAERI	7.292E-3	7.279E-3



(a) Bird's eye view



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.

(b) Assembly cross section

Fig. 1 Outlook of the VHTRC assembly

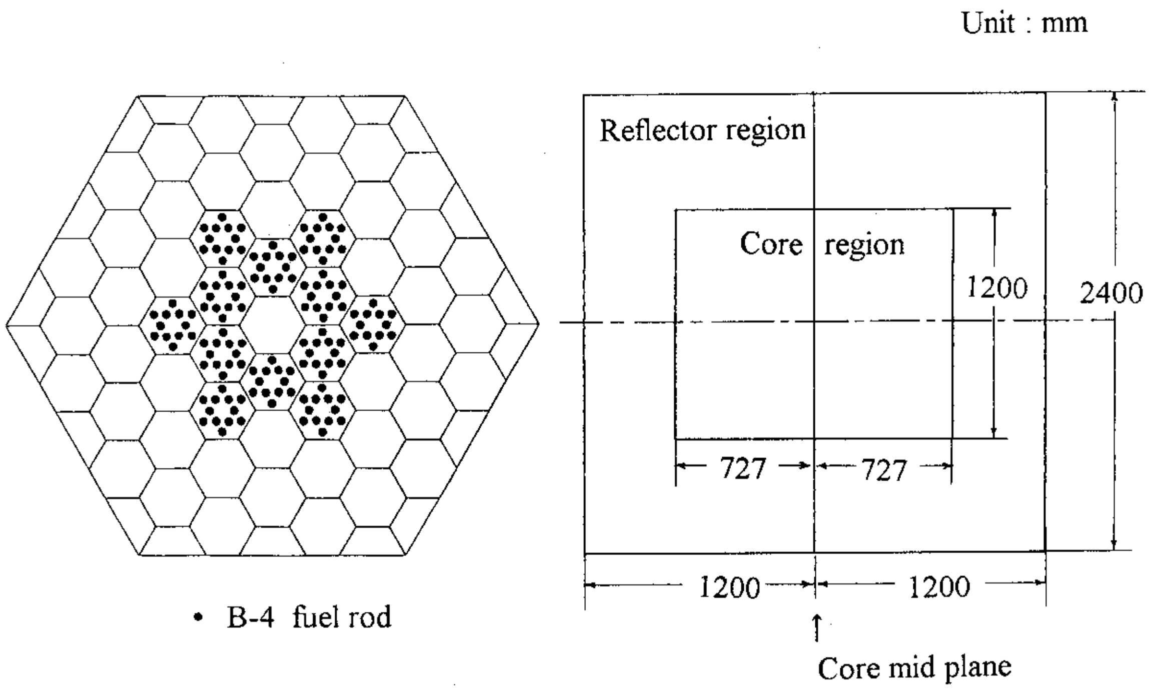


Fig. 2 Modeled core fuel loading pattern of VH1-HP and the first step of VH1-HC

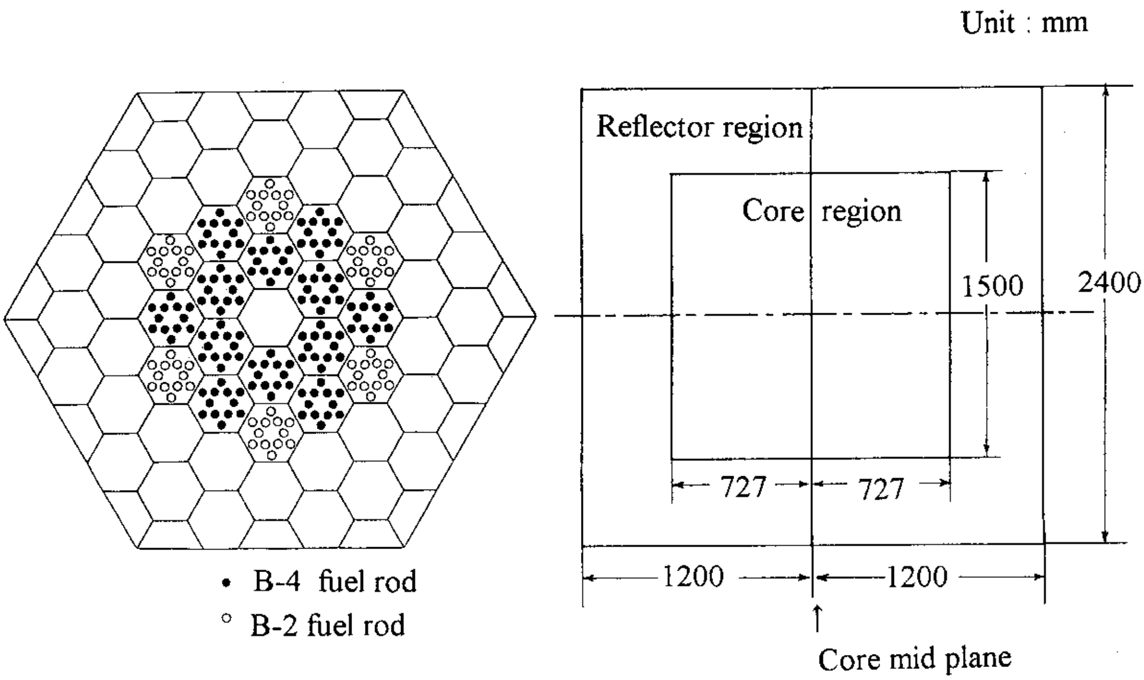


Fig. 3 Modeled core fuel loading pattern of the second step of VH1-HC

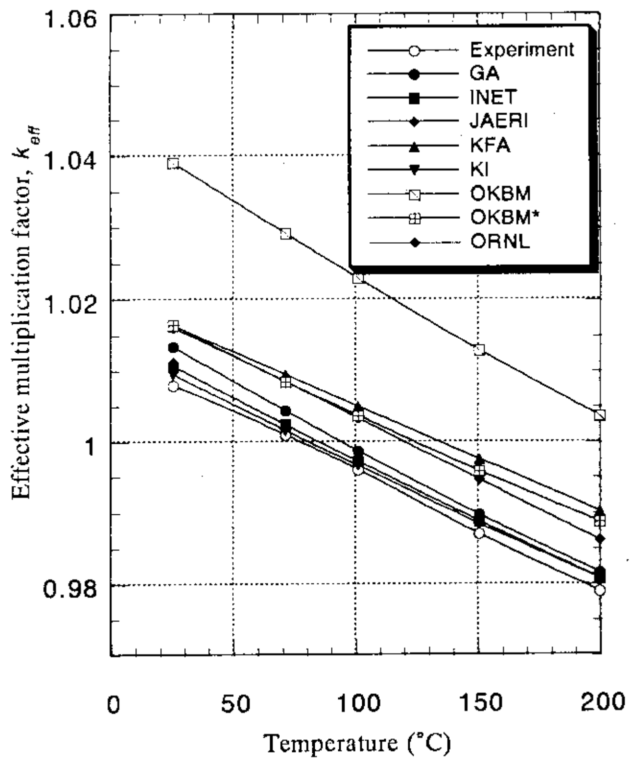


Fig. 4 Effective multiplication factor versus average assembly temperature

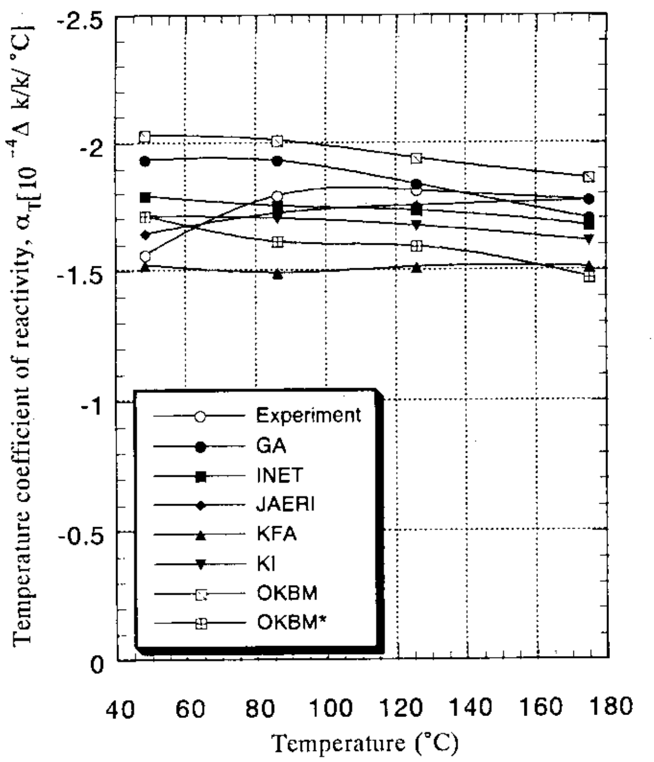
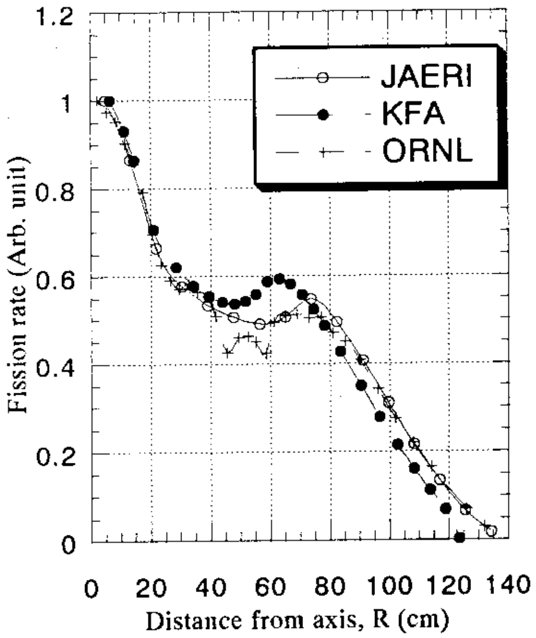
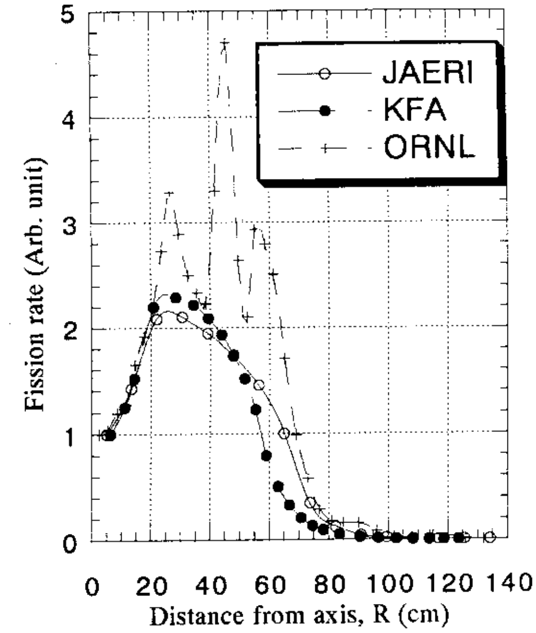


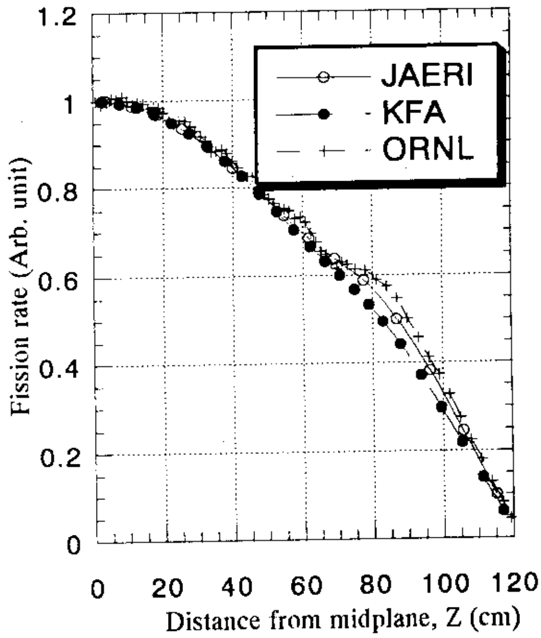
Fig. 5 Temperature coefficient of reactivity versus average assembly temperature



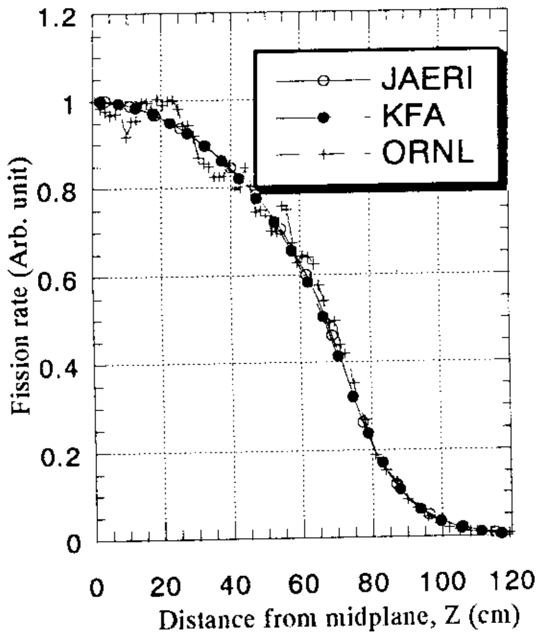
(a) Radial distribution of ^{235}U fission



(b) Radial distribution of ^{238}U fission

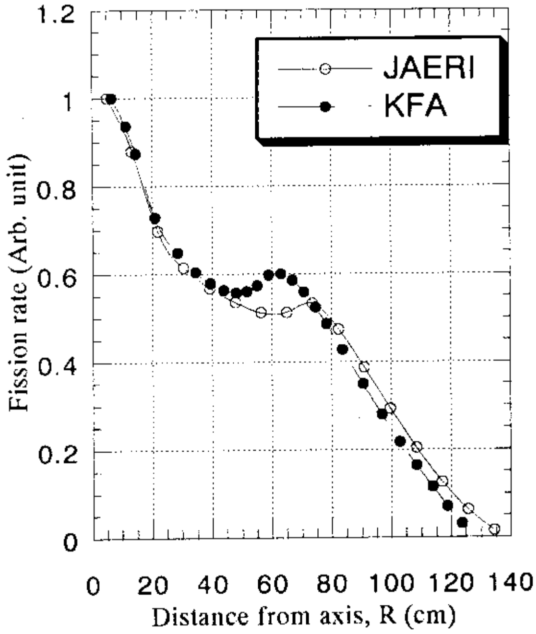


(c) Axial distribution of ^{235}U fission

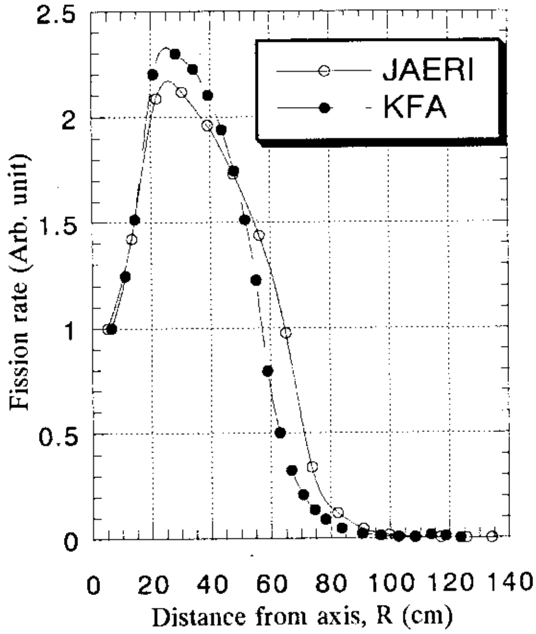


(d) Axial distribution of ^{238}U fission

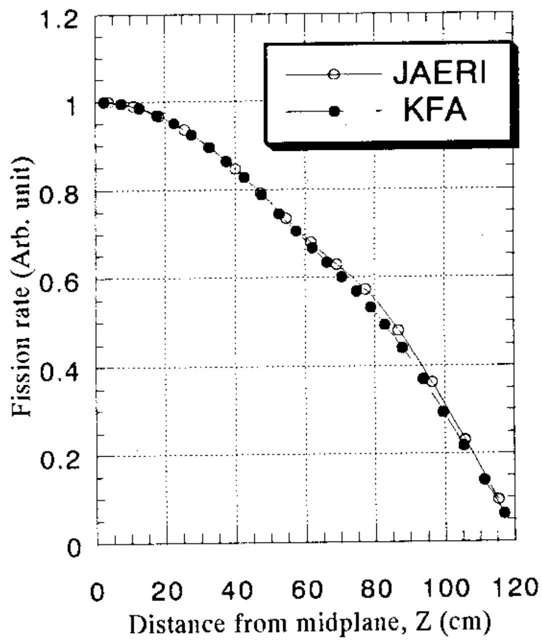
Fig. 6 Fission distributions for VH1-HP, 25.5 °C, calculated using effective cross sections of B-4 type cell



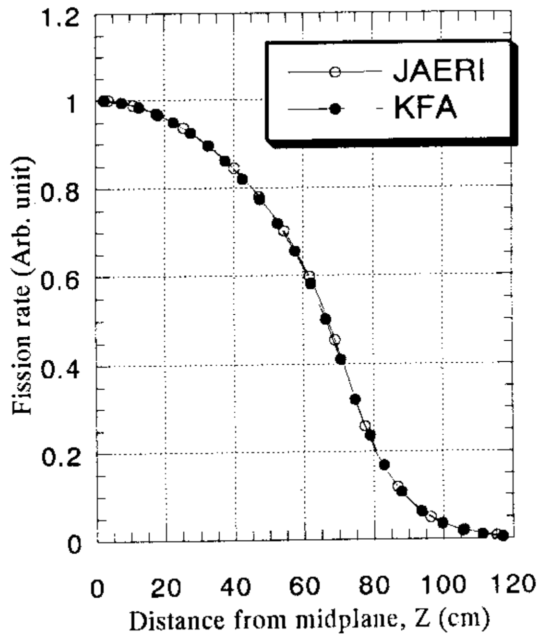
(a) Radial distribution of ^{235}U fission



(b) Radial distribution of ^{238}U fission

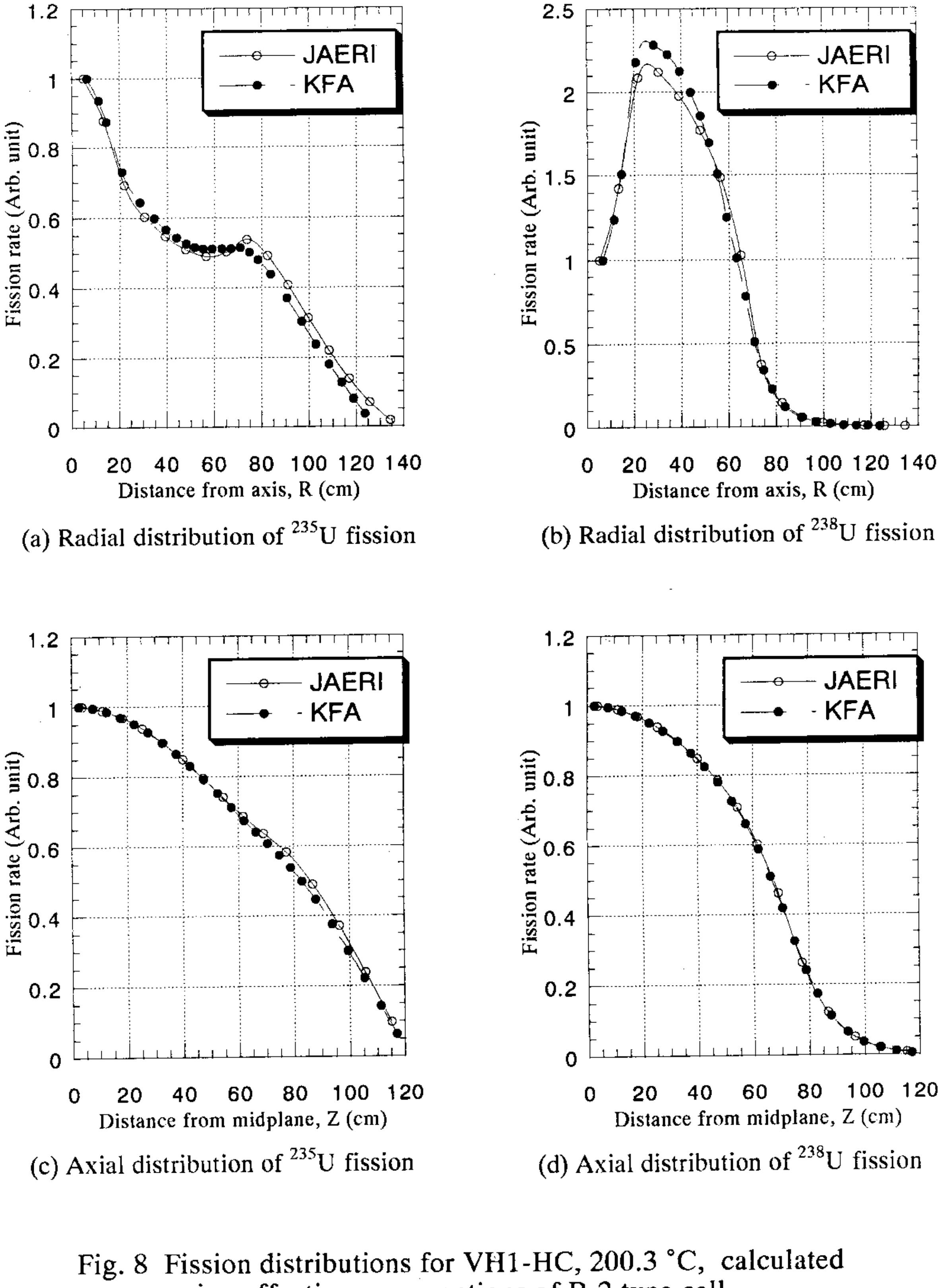


(c) Axial distribution of ^{235}U fission



(d) Axial distribution of ^{238}U fission

Fig. 7 Fission distributions for VH1-HP, 199.6 °C, calculated using effective cross sections of B-4 type cell



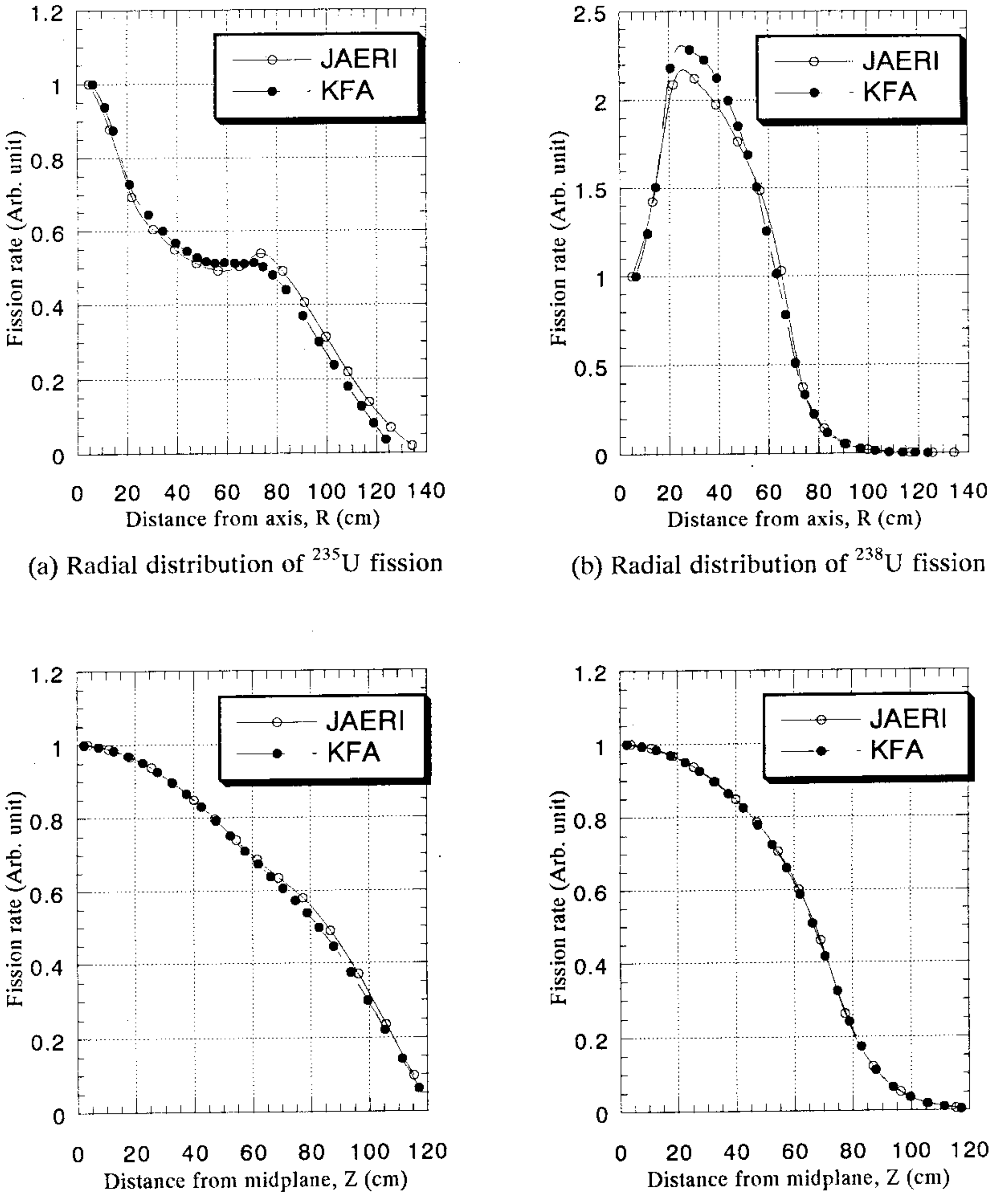
(a) Radial distribution of ^{235}U fission

(b) Radial distribution of ^{238}U fission

(c) Axial distribution of ^{235}U fission

(d) Axial distribution of ^{238}U fission

Fig. 8 Fission distributions for VH1-HC, 200.3 °C, calculated using effective cross sections of B-2 type cell



(a) Radial distribution of ^{235}U fission

(b) Radial distribution of ^{238}U fission

(c) Axial distribution of ^{235}U fission

(d) Axial distribution of ^{238}U fission

Fig. 9 Fission distributions for VH1-HC, 200.3 °C, calculated using effective cross sections of B-4 type cell