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Division d'Etudes et de Développement des Réacteurs
Centres d'Etudes Nucléaires de Cadarache et de
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EXPERIMENTS IN PURE URANIUM LATTICES WITH UNIT K_∞.

ASSEMBLIES SNEAK-8/8Z; UK 1 AND UK 5 IN ERMINE AND HARMONIE

Compiled by

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Experiments in Pure Uranium Lattices with unit k_∞.

Assemblies SNEAK-8/8Z; UK 1 and UK 5 in ERMINE and HARMONIE

Abstract

Physics measurements in pure uranium lattices with k_∞ (production/absorption) close to unity were carried out in the critical facility SNEAK at KARLSRUHE (cores 8 and 8Z), the fast thermal coupled facility ERMINE at FONTENAY-AUX-ROSES (cores UK 1 and UK 5) and the exponential experiment HARMONIE at CADARACHE (core UK 5).

k_∞ was experimentally determined from the central cell worth (SNEAK and ERMINE) or from the material buckling (HARMONIE). The reaction rate ratios were measured using the techniques developed at the different laboratories. In addition, the differential neutron spectrum was measured in some assemblies.

All the experimental results were analyzed using the GfK and CEA methods, thus providing an extensive intercomparison of experimental techniques on one side, and of cross section data on the other side.

The experimental results were then combined, and extrapolated to obtain best estimates for the parameters of a pure homogeneous uranium medium of exactly unit k_∞. This medium is proposed as a standard for nuclear data testing.

29.3.1974

Etudes expérimentales de réseaux en uranium metallique pur à k_∞ voisin de 1'unité: Assemblages SNEAK-8/8Z, ERMINE et HARMONIE UK 1, UK 5

Sommaire

L'étude expérimentale de milieux en uranium pur, tels que k_∞ (production/absorption) soit proche de 1'unité, a été realisée dans 1'assemblage critique SNEAK à KARLSRUHE (coeurs 8 et 8Z), 1'expérience couplée rapide thermique ERMINE à FONTENAY-AUX-ROSES (coeurs UK 1 et UK 5) et 1'expérience exponentielle HARMONIE à CADARACHE (coeur UK 5).

k_∞ a été déterminé expérimentalement à partir de mesures d'effet en reactivité de cellules centrales (SNEAK et ERMINE) ou de laplacien matière (HARMONIE). Les indices de spectre ont été obtenus par les techniques developpées dans les differents laboratoires. En outre, le spectre neutronique différentiel a été mesuré dans certains assemblages.

Tous les résultats expérimentaux ont été analysés par les methodes utilisées à GfK et au CEA, permettant ainsi d'effectuer une intercomparaison approfondie des techniques expérimentales d'une part, et des jeux de sections efficaces d'autre part.

Les résultats expérimentaux ont alors été mis en commun, puis extrapolés, afin d'obtenir une meilleure estimation des paramètres d'un milieu homogène en uranium pur de k_∞ exactement égal à 1'unité. Ce milieu est proposé comme standard, pour permettre de tester les données nucléaires de base.

Experimente in reinen Uran-Anordnungen mit k_∞ gleich eins. Anordnungen SNEAK-8/8Z, UK 1 und UK 5 in ERMINE und HARMONIE

Zusammenfassung

Reaktorphysikalische Messungen in reinen Uran-Zellen mit k_∞ nahezu gleich eins wurden in der schnellen kritischen Anordnung SNEAK (Core 8 und 8Z) in KARLSRUHE, in der schnell-thermischen Anordnung ERMINE (Core UK 1 und UK 5) in FONTENAY-AUX-ROSES und in der Exponential-Anordnung HARMONIE (Core UK 5) in CADARACHE durchgeführt.

k_∞ wurde experimentell aus dem zentralen Zellwert (SNEAK und ERMINE) oder aus dem materiellen Buckling (HARMONIE) bestimmt. Die Ratenverhältnisse wurden nach den in den verschiedenen Labors entwickelten Meßtechniken bestimmt. In einigen Anordnungen wurde auch das differentielle Neutronenspektrum gemessen.

Alle experimentellen Ergebnisse wurden bei GfK und bei CEA nachgerechnet. Damit konnte ein umfassender Vergleich sowohl der Meßmethoden, als auch der Wirkungsquerschnittssätze durchgeführt werden.

Durch Zusammenfassung aller Meßergebnisse und durch eine kleine Extrapolation wurden Best-Werte für die Parameter des reinen Uran-Mediums, für das k_∞ genau gleich eins ist, gefunden. Es wird vorgeschlagen, das so definierte Medium als Standard zum Testen von Querschnittsdaten zu verwenden.

TABLE OF CONTENTS

I. INTRODUCTION

Following a proposal of the U.K.A.E.A., uranium lattices similar to ZEBRA-8H in Winfrith (U.K.), with k_∞ near unity, were studied in the critical facilities SNEAK at Karlsruhe, ERMINE at Fontenay-aux-Roses, and HARMONIE at Cadarache. There are several reasons for building similar assemblies at the different laboratories. First, they provide the possibility for a valid and reliable intercomparison of experimental techniques, especially on the calibration of reaction rate measurements. Second, the balance of reaction rates provides an integral check on the consistency between measured k_∞ and reaction rates, and calculated α_5, and thus allows an additional statement on the reliability of the results obtained at each laboratory. Third, the experimental results of all the laboratories can be combined to determine, by a slight extrapolation, the best values of the enrichment and spectral indices of a homogeneous uranium medium with k_∞ equal to unity. These data, which are derived as a weighted mean from different experiments, can be given a high degree of confidence, and they are proposed as standard for nuclear data testing.

The lattices under study consisted of metallic uranium, either in the form of plates or rods, with a minimum of diluents, and with an average enrichment such that k_∞ was close to unity. They were built as test zones with drivers that were quite different in the different facilities. All the test zones were large enough that the equilibrium spectrum was nearly established at the center.

The experimental program was focused on the measurement of k_∞, buckling, reaction rate ratios, and the differential neutron spectrum. Some additional experiments were also carried out in each assembly.

In a lattice of this type, k_∞ can be determined accurately from the measured reactivity worth of the unit cell against a void. This so-

called PCTR-technique, though originally developed for thermal reactors, was also used extensively in fast critical facilities in the past /1/. Besides, k_∞ can also be determined from measurements of the material buckling. The measured k_∞, in combination with measured reaction rate ratios, provides a good integral test on the theoretical predictions. Also, as the leakage is negligibly small, one can in principle infer the capture rate in ^{235}U, which cannot be measured directly, from the neutron balance. However, in the lattices under study the ^{235}U capture rate is very small; on the other hand, fairly large uncertainties exist in the measurement of the capture rate in ^{238}U. In this case, the balance can be considered as an integral check on the consistency between the measured capture rate in ^{238}U, and α_5 (ratio capture to fission) obtained from basic data.

A further goal of these lattices was a rather detailed comparison of experimental results with predictions using the standard methods and data at the different laboratories. Only cell calculations are needed, because the parameters are defined for the equilibrium spectrum. The comparison gives information on the cross section data, primarily the inelastic scattering of ^{238}U, as this is the dominant mechanism of neutron degradation in these cores.

As mentioned already, the results from all these cores were combined to determine best values for the minimum critical enrichment, and the reaction rate ratios. These data may be used as a standard for nuclear data testing.

A slightly different standard, which was presented in a separate publication /2/, should also be mentioned here. It was derived from a series of k-infinity lattices studied in European laboratories, which includes, besides the cores described in this report, the assembly ZEBRA-8H in Winfrith. The two standards differ by less than one standard deviation.

II. DESCRIPTION OF THE ASSEMBLIES

II.1. Unit cells of the test zones

II.1.1. SNEAK-8 and 8Z

In SNEAK, the core materials are in the form of platelets with square cross section 5.077 x 5.077 cm^2, and thickness of 0.314 cm, and 0.157 cm. The uranium platelets are coated with nickel. The plates are stacked horizontally in vertical subassembly tubes of stainless steel, which are suspended from a grid plate. The lattice pitch is 5.44 cm.

The unit cell of the test zone SNEAK-8 was designed such that k_∞ was as close to one as possible, with a unit cell of reasonable thickness. The cell consisted of 2 platelets of 20% enriched uranium, 5 platelets of natural uranium, and one platelet of depleted uranium (Fig. II-1). The average enrichment was 5.87%.

In SNEAK-8Z, the two 20% uranium platelets were replaced by one 35% enriched uranium platelet (Fig. II-1). This unit cell had a higher enrichment of 6.03%, and a larger heterogeneity than the SNEAK-8 cell. It was designed to match the unit cell of the assembly ZEBRA-8H at Winfrith as closely as possible. The availability of results from ZEBRA-8H were a great help in the design of the SNEAK cells.

The compositions of the test zones are given in Table II-1. The atom densities used for heterogeneous cell calculations are given in Appendix I.

II.1.2. ERMINE UK 1, ERMINE-HARMONIE UK 5

In ERMINE and HARMONIE, the core materials are in the form of rods: depleted uranium rods of square cross section (12.7 x 12.7 mm^2) or 30% enriched/depleted uranium rods of circular cross section (diameter 12.7 mm or 6.35 mm). These rods are coated with nickel.

The rods are loaded into stainless steel tubes of 0.7 mm wall thickness and of 52.5 x 52.5 mm^2 square cross section. The lattice pitch is 53 mm.

The two following lattices were studied in ERMINE and HARMONIE (Fig. II-2):

- ERMINE UK 1 — The unit cell is fairly complicated but k_∞ is very close to unity. The average enrichment is 5.81%.

- ERMINE and HARMONIE UK 5 — The very simple unit cell allows a good interpretation of spectral indices and heterogeneity measurements but k_∞ is 1.06. The average enrichment of the cell is 6.60%.

The compositions of the test zones are given in Table II-1. The atom densities of the different zones used for heterogeneous cell calculations are given in Appendix I.

II.2. Design of the critical cores

II.2.1. SNEAK-8 and 8Z

The test zone of SNEAK-8 was 58.8 cm high, and its radius was 32.0 cm. This size was large enough that the spectrum in the central region, where the measurements were made, was close to equilibrium. On the other hand, the composition of SNEAK-8Z was loaded only as an inner zone in the central 37 SNEAK subassemblies, with an average radius of 18.7 cm, over a height of 40.7 cm. The rest of the test zone region had the composition of SNEAK-8. However, as the compositions differ very little, spectral transients were negligible.

In the critical core SNEAK-8, the test zone was surrounded both in axial and radial direction by a highly reactive driver zone, and by a blanket of depleted uranium.

The radial driver zone had a thickness of about two subassemblies. The unit cell consisted of 4 platelets of 35% enriched uranium, and 7 graphite platelets (Fig. II-1). The axial driver zone, both on top and bottom of the test zone, had two normal driver zone cells, plus a "rest cell" which contained 3 platelets of 35% enriched uranium, and 5 graphite platelets. The minimum blanket thickness was 30 cm.

The core cross sections in X-Y- and in R-Z-geometry are shown in Fig. II-3, II-4, and II-5. These figures also show the position of the shim rods, and safety rods. The rods had an additional inner tube, which can be moved in vertical direction. In the operating position, these tubes were filled with core material, with an average density reduced to about 84%. By the presence of the inner tube, the steel content was higher by a factor of 1.95 than in a normal SNEAK-subassembly.

Four driver subassemblies at the corners (A in Fig. II-3) were used to adjust criticality. Their loadings were varied for different experiments. In one case, they contained half the amount of fuel plates of a standard driver element, in a second case only about one fourth (see Section IV.).

Table II-2 shows the atom densities of the driver zone, averaged over the standard cell. The average densities for the radial driver zone, with the control rods homogenized, are also shown. In addition, the table gives the atom densities of the blanket.

II.2.2. ERMINE UK 1 and UK 5

The lattices UK 1 and UK 5 were investigated in the fast-thermal critical facility ERMINE /3/ installed in the reactor MINERVE in FONTENAY-AUX-ROSES.

MINERVE /4/ is a zero-power swimming-pool reactor, having in its center a square cavity, the diameter of which can be varied from 0 to 900 mm.

The fast-thermal critical assembly ERMINE UK /5/ consisted of a central fast zone and buffer (placed in a water-proof stainless steel tank), and of the thermal zone and reflectors of the reactor MINERVE.

The core cross sections in X-Y- and in R-Z-geometry for both cores are shown in Fig. II-6 and II-7.

A. The central zones

The central portion of the assembly contained two zones:

1) The test zone was approximately cylindrical, 60 cm in height and 16 cm in equivalent radius.

Remark: In regard to the UK 1 lattices, it was not possible to build a test zone 60 cm in height entirely with UK 1 cells, because of the lack of material. Therefore UK 2 cells, described in Fig. II-2, were utilized as supplements. Their enrichment and k_∞ were very close to those of UK 1 (E = 5.96%, k_∞ = 1.01) but their density was lower.

2) The buffer: 7 cm thick, 60 cm high. Its purpose was to convert the reactor thermal neutron flux into a central spectrum as close as possible to the fundamental mode spectrum of the reference medium.

The buffer consisted of two parts:

- a low-enriched uranium converter (UK 5 in this case) that filters thermal neutrons.
- an adaptative zone consisted of ^{238}U for the purpose of softening the fission spectrum from the converter by inelastic scattering.

Both test zone and buffer were placed at the center of the tank.

Graphite elements were used to fit the central zone to the geometry of the tank (Fig. II-6).

B. The thermal zone

The thermal zone was a light water moderated lattice. The fuel consisted of aluminium and 90%-enriched uranium plates.

A graphite reflector surrounded the core.

The safety rods and the fine control rod were placed in the thermal zone (Fig. II-6).

Table II-3 gives the atom densities of the different regions.

II.2.3. The exponential experiment HARMONIE UK 5

The study of the lattice UK 5 was also performed in the exponential experiment HARMONIE /6/.

HARMONIE is a fast neutron low-power source-reactor. The core is a cylinder of 93% enriched metallic uranium, 123 mm in diameter and 129 mm in height. It is surrounded by a depleted uranium blanket and by a stainless steel reflector, each 10 cm thick.

The exponential assembly is a prism of 53 x 53 cm^2 square cross section and 90 cm height, built with 10 x 10 stainless steel tubes.

The lattice pitch is 5.3 cm (Fig. II-8).

The assembly was placed vertically above the HARMONIE core. In order to reduce the number of reflected neutrons, the biological shields were removed during the measurements.

II.2.4. Summary table

The main characteristics of the different lattices are shown in the following table.

Core		UK 1[a] ERMINE	SNEAK-8	SNEAK-8Z[b]	UK 5 ERMINE	UK 5 HARMONIE
Test Zone	Volume (l)	51.4	189.6	189.6	51.4	285
	Mass of ^{235}U (kg)	43.3	174.6[c]	175.8[c]	53.3	296
	Mass of ^{238}U (kg)	702	2835[c]	2834[c]	762	4233
Driver	Radial	Thermal zone	Fast driver zone	Fast driver zone	Thermal zone	--
	Axial	--			--	HARMONIE
Adaptation zone		Yes	No	No	Yes	No

a) Including the UK 2 zone

b) Including the SNEAK-8 test zone

c) Note that the control rods contain less U than the standard cell of Table II-1

III. NOTE ON THE CALCULATIONAL METHODS AND CROSS SECTION SETS

III.1. Cross section sets

III.1.1. G f K

At GfK, the measured integral parameters were calculated with the two most recent cross section sets developed at Karlsruhe, MOXTOT and KFKINR. Both cross section sets have the 26-group structure of the well-known Russian ABN-Set, and also use the concept of the composition-dependent resonance self-shielding factors. The MOXTOT set is documented in /7/, the KFKINR set in /8/. The major differences in the nuclear data basis of the two sets are the following:

a) Whereas MOXTOT uses a universal fission spectrum, KFKINR calculates the fission spectrum for each composition from the contributions of the isotopes present.

b) In the KFKINR set the inelastic scattering cross section of ^{238}U is about 20% lower than in the MOXTOT set. In addition, the average energy loss per inelastic scattering event is smaller.

c) The ^{239}Pu fission cross section is higher in the KFKINR set. Also, the ratio capture to fission is slightly higher.

d) The capture cross section of ^{238}U, which is very low in MOXTOT (MOXON data), was increased in the range 100 keV - 800 keV for the KFKINR set.

Recent experience has shown that KFKINR calculates integral data much better than MOXTOT. The parameters of the uranium lattices described

in this report are especially sensitive to the change in σ_{in} of ^{238}U. The experimental design was made only with the MOXTOT set.

III.1.2. C E A

The cross section set used is the version 2 CADARACHE set. It was obtained by a statistical adjustment to integral experiments /9/. The elastic scattering matrices of the light weight elements are treated in 600 energy groups. The other reactions do not require such accurate calculations; they are treated in 25 energy groups.

At the present time a new version of the set (version 3 CADARACHE) /10/ is being prepared. It is adjusted to several parameters measured in MASURCA, HARMONIE, ERMINE and SNEAK experiments during the last four years.

The comparative results are given in Chapter VII.

III.2. Calculations for the test zones

III.2.1. G f K

The integral parameters of the SNEAK test zones were calculated in 26 energy groups, and in zero dimensions with the cell code ZERA, and also with the KAPER code /11/, which was developed recently from the older ZERA code. Both codes gave results which are practically

identical. The CEA cores, with the unit cell approximated by cylindrical geometry cells, were calculated with ZERA only, because KAPER cannot be used for cylindrical cells. Both codes use the collision probability method, and account for resonance self-shielding by a procedure which can be considered as an extension of the classical equivalence theorem /12/.

III.2.2. C E A

The integral parameters of unit cells are calculated with the HETAIRE code /10/ which solves the transport equation using the collision probability method.

- The cell heterogeneity may be resolved in cylindrical or plane geometry.

- The elastic scattering matrices of the light elements are calculated in 600 energy groups, and are then condensed into 25 energy groups.

- The "subgroup" method /13/ is used to calculate the resonance self-shielding of the heavy isotopes in 25 energy groups.

- The code allows to calculate the macroscopic cross sections of the homogeneous equivalent cell, for use in spatial calculations.

III.3. Spatial calculations

III.3.1. SNEAK

One-dimensional diffusion theory in spherical geometry was used to calculate the full assembly with test zone, driver zone, and blanket. The influence of the spectrum mismatch due to the presence of the driver zone, and the dependence of the cell parameters on the eigenvalue λ (see Appendix II) were studied by these one-dimensional calculations. However, in order to analyse the measured fission rate traverses, the two-dimensional diffusion code DIXY was used.

III.3.2. ERMINE

The spatial calculations of the fast-thermal assembly ERMINE were performed in cylindrical geometry with a one-dimensional transport code (DTF4 /14/). For these calculations, the macroscopic cross sections from the HETAIRE code were used. The axial leakage was taken into account in the form of fictitous capture cross sections equal to DB^2 (where B^2 is constant).

Thus, an average spatial flux was calculated. In order to obtain the heterogeneous spatial flux, the fine structure of the fundamental flux in the cell was applied:

$$\phi^{i}_{\text{spatial}}(E) = \overline{\phi}_{\text{spatial}}(E) \cdot \left[\frac{\phi^{i}_{F}(E)}{\overline{\phi}_{F}(E)} \right]$$

index F: fundamental mode

index i: index of the region in the cell

In fact the one-dimensional transport calculation did not exactly take the axial leakage of the core into account. One additional correction was applied which was estimated in diffusion theory using a comparison between two calculations. These were:

- One-dimensional diffusion calculation, where the axial leakage was treated in the same manner as in the transport calculation.

- Two-dimensional diffusion calculation.

This correction α_x is generally very small and is applied to the measured parameters which may be, in this manner, compared to a one-dimensional calculation.

$$\alpha_x = \frac{x \text{ (one-dimensional calculation)}}{x \text{ (two-dimensional calculation)}}$$

where x is the investigated parameter (k^+, k^*, reaction rate ratios).

III.3.3. HARMONIE

The spatial calculations were performed using one-dimensional transport theory. The validity of these results was tested by comparison with two-dimensional transport calculation where the criticality was obtained by adjusting the size of the HARMONIE core.

The macroscopic cross sections of the homogeneous equivalent medium came from the HETAIRE code. An average flux was obtained in the asymptotic zone. As for the ERMINE calculations the fine structure of the fundamental flux was applied in order to obtain the heterogeneous spatial flux.

IV. MEASUREMENTS OF k_∞ and B^2

IV.1. Principle

IV.1.1. k_∞ measurements

The so-called PCTR technique to measure the multiplication factor in a zone where k_∞ is close to 1 is based on the observation that the reactivity worth of the unit cell at the core center is proportional to the leakage, and is, therefore, proportional to $k_\infty - 1$. In the measurements reported in this paper, the worth of the unit cell was normalized to the worth of ^{235}U, because this ratio can be better measured and calculated in a zoned core than the absolute worth. Then, one obtains a relation of the type

$$k_\infty = 1 + m \frac{\delta k_{cell}}{\delta k_{U5}} + \varepsilon \qquad (4\text{-}1)$$

where m and ε must be calculated. ε is a small correction for the spectrum mismatch due to the influence of the driver zone.

The worth of the unit cell consists of the worth of the core material (plates or rods) and the worth of the structure, which must be determined by separate measurements. In practice, the PCTR technique works well in a fast reactor if k_∞ is close enough to unity (about 3% or better); then errors in the calculated coefficient m do not seriously affect the accuracy of the results. The theoretical considerations involved in the conversion of the worth of the unit cell to k_∞ are outlined in Appendix II.

IV.1.2. Buckling measurements

The experimental buckling was obtained from fission rate distributions measured with different kinds of fission chambers. In the exponential experiment, the buckling was determined as the difference:

$$B_M^2 = B_T^2 - \gamma^2$$

It is possible, using the calculated value of the migration area M^2, to obtain the k^* of the medium, using the relation:

$$k^* = 1 + M^2 B^2.$$

IV.2. Description of the experiments

IV.2.1. Cell worth measurements

1) SNEAK

a) Method of the measurements: The reactivity change due to removal of material was measured in most cases with the calibrated fine control rod in position 11/26. The rod worth was about 4 ¢, and its characteristic was nearly linear. In some measurements, where the reactivity change was large, the shim rod in position 23/17 was also used; it was worth 52 ¢. Both rods were calibrated with an inverse kinetics method. The errors, mainly due to reproducibility error (±0.02 ¢) and error in the rod characteristic, are of the order of 1 to 2%.

The worths of the plate cell, of stainless steel, and of enriched uranium were measured at the core center of SNEAK-8 and 8Z. 9 special subassembly tubes were used, with vertical windows cut in one side of the tube. The windows were positioned around the axial midplane of the core; they were wide enough so that the uranium platelets could be removed without unloading the whole subassembly. Thus, a cavity could be created at the core center. The platelet loading above the cavity was supported by a SS frame which was fixed to the subassembly tube.

The worth measurements were carried out in a region of 15 cm diameter (9 subassemblies), and about 20 cm axial height. In this region, the spectral transients were small, and did not impair the results. The arrangement of platelets in the special subassembly is shown in Fig. IV-1 and IV-2. The upper two cells in SNEAK-8 (3 in 8Z) were composed of half-platelets (cross section 5.077 x 2.538 cm^2) which could be removed while having only a small distance from the SS frame.

b) Reactivity worth of the plate cell: In order to investigate the dependence of the plate worth on the size of the cavity, reactivity measurements were made for cavities of 3 different heights in all 9 subassemblies, and also in the 4 subassemblies at the corners (1 to 4 in Fig. II-3). The results are shown in Table IV-1. They are corrected for the slightly different composition of the half-platelets[+]. All the results are consistent within about 2 standard deviations. Thus, as one would expect for a hard spectrum core, the dependence of the cell worth on the size of the cavity is certainly very small.

[+] Note that all the uncertainties quoted in this paper correspond to one standard deviation (1σ).

However, their seems to be a tendency for the worth in the 4 elements to be slightly higher than in all 9 elements. This tendency is also predicted by calculation, and is therefore, probably real, though rather small. The reason is that the negative worth of stainless steel decreases with increasing thickness. Thus, when the platelets are taken out in 9 subassemblies, the empty SS tubes form a lattice with a rather large optical thickness, which has a reduced worth. Thus, the measured reactivity change upon removal of the cells is slightly reduced.

The standard core SNEAK-8 was about 24 ¢ supercritical. In this configuration, the four driver subassemblies A (Fig. II-3) were loaded with half the fuel material of a normal driver cell. The excess reactivity was shimmed with the rods 11/23 and 23/17, which means that driver zone material was replaced by blanket material near the top of the core. The fission chamber traverses measured in this configuration indicate a flux gradient in axial direction, which was attributed to the influence of the shim rods. It was estimated that this gradient would have only a small effect on the cell worth (see estimate in the Appendix III.). However, to verify that this was correct, some additional measurements were carried out in a "clean core", where the fuel loading of the driver subassemblies A (Fig. II-3) was reduced to one fourth of the normal loading. In this "clean core", only 5 ¢ had to be shimmed with the rod 23/17. The reactivities normalized to ^{235}U agreed within experimental errors with the ones in the "standard core". In SNEAK-8Z, about 10 ¢ was shimmed with the rod 23/17.

c) Reactivity worth of the stainless steel tube: The worth of stainless steel was measured by inserting samples of tube material with a total weight of 1200 g in the cavities of the four corner elements. This way, the four samples were separated from each other, and one avoided to have a layer of stainless steel with a large optical thickness. The results are also given in Table IV-1.

In order to check the dependence of the steel worth on the sample size, a measurement with a total of 2400 g of steel in the 4 subassemblies was also made. The worth was -1.045×10^{-5} \$/g, which is about 3% lower than the value obtained with the smaller samples. However, the latter was considered more representative of the contribution of the steel tubes to the worth of the unit cell.

d) Normalization: The worth of ^{235}U was obtained from measurements in the four corner elements, where enriched uranium platelets were replaced by natural uranium platelets. The correction for the worth of ^{238}U was rather small.

The uncertainties quoted in Table IV-1 are experimental errors, which are due to reproducibility, and control rod calibration.

2) ERMINE

a) Method of measurements: The reactivity measurements were performed by the oscillation technique. The reactivity variations were compensated by a high precision fine control rod, placed in the thermal zone. Its total worth was of the order $4 \times 10^{-4} \frac{\delta k}{k}$ and its maximum differential effect was about of $5 \times 10^{-5} \frac{\delta k}{k}$ per angular degree.

The samples were moved by a vertical electro-mechanical oscillator.

The oscillator tube consists of a stainless steel structure, 2 m in height.

The oscillator movement is pseudo-square with a period of 60 sec, and an amplitude of 600 mm.

The reactivity change was obtained from the angular position of the compensating fine control rod, which was driven by an "on-line" computer. Data obtained during transit times were suppressed.

In order to avoid systematic errors due to a possible nonuniform loading of the oscillator tube, the worth of a sample was always obtained by difference between two measurements, one with the sample in the tube, and the other without the sample.

b) Cavity: The oscillator tube was loaded with MASURCA uranium rods. When the oscillator was at either end of its stroke, the portion of the oscillator in the core was loaded with core material.

The rods of the cell were removed to create a void. Aluminium spacers (two plates and one tube) were inserted in place of the removed rods to hold the fuel above the perturbed region (Fig. IV-3).

c) Reactivity worth measurements: The worth of the rods was measured by the difference between the signal obtained when the oscillator tube was completely loaded and the signal when the void was created.

- Worth of the UK 1 rod cell — The worth was obtained by removing the fuel over a 101.6 mm height (MASURCA rod length).

- Worth of the UK 5 rod cell — The worth of the UK 5 rod cell was obtained by removing the fuel over 20, 40, 60, 80 and 101.6 mm height.

The results are summarized in Tables IV-2 and IV-3[+].

d) Additional measurements and corrections: In order to obtain the worth of the fuel, the measurements for the different sizes of cavity were corrected to take into account the perturbations due to:

- the aluminium spacers
- the possible flux gradient in the center of the test region
- the slightly different composition between the removed rods and the average rods of the test region.

The worth of the unit cell was then obtained by adding the worth of the associated steel sheath.

The different corrections are given in Tables IV-2 and IV-3.

- Worth of steel and aluminium — The worth of steel and aluminium was obtained from measurements with steel and aluminium samples of various geometry (rods or tubes), inserted into the space created by removal of the fuel rods. The experimental error was about ±3%.

+) Note that all the uncertainties correspond to one standard deviation (1σ)

- Flux gradient

The flux in the center of ERMINE was not flat (axial gradient due to the small height of the core; radial gradient due to the imbalance of the thermal zone loading).

The flux gradient was obtained from the experimental reaction rate traverses (see Appendix III.).

The radial portion of this correction was experimentally tested in UK 1 by measurements for 3 thermal zone configurations (Table IV-2).

The axial portion was tested in another lattice, in ERMINE, with k_∞ close to unity.

Nevertheless an uncertainty of ±15% was considered for this correction.

- Correction for composition

The composition of the uranium rods used in the cell worth measurement was not exactly equal to the average of the test region. A correction, generally very small, obtained by measuring the reactivity worth of the cell components was applied.

- Correction for heterogeneity

In the UK 5 lattice, the reactivity of the cell was measured for different sizes of the cavity. No size dependence was found experimentally (Table IV-3).

e) Normalization: All the reactivity worth measurements were related to the worth of the ^{235}U content of the cell.

The ^{235}U worth, as well as the ^{238}U worth was found by replacing 30% enriched uranium rods by identical geometry rods with a lower density or enrichment. The self-shielding variations and the perturbed flux in those rods were accounted for by calculations.

The accuracy of the ^{235}U worth measurements was about 1%.

3) Results

The worth of the core material, and of stainless steel were combined to give the worth of the unit cell. The results are listed in Table IV-4. All the worths in this table are normalized to the worth of ^{235}U in the cell.

Note that the error of the stainless steel worth, as quoted in Table IV-4 was increased by about 2% above the experimental error (Table IV-1), to cover the uncertainty due to the fact that the stainless steel worth measurements could not be performed in the actual geometry of the core. The steel worths in Table IV-2 and IV-3 are quoted with errors accordingly increased (see page 30).

IV.2.2. Experimental buckling determination

1) Description of the measurements

Fission rate distributions were measured in the exponential experiment UK 5 with fission chambers (^{235}U, ^{239}Pu, ^{237}Np and ^{238}U) in vertical and horizontal channels (Fig. II-8).

a) The vertical channel was placed at a distance of 27 mm from the axis of the assembly. The channel was built by replacing a column of depleted uranium with a guiding tube.

b) The horizontal channels also had a square cross section and replaced the depleted uranium. Measurements were performed in three positions:

channel 1H at 30.48 cm from the base
channel 2H at 40.64 cm from the base
channel 3H at 50.80 cm from the base.

2) Results

The method of obtaining the relaxation constant and the radial cosine distribution at different positions is described in /15/:

- least - squares fitting of the experimental traverses
- least - squares fitting of the calculated traverses, using the flux obtained from a one-dimensional transport calculation
- regression between calculated and experimental values in order to obtain the experimental value corresponding to the "adjoint-flux detector".

The experimental traverses are given in Figs. IV-4, IV-5, IV-6 and IV-7.

The experimental values obtained for the material buckling at the various heights are the following:

	B_T^2 (m^{-2})	γ^2 (m^{-2})	B_m^2 (m^{-2})
channel 1H	53.56 ± 0.09	43.67 ± 0.07	9.89 ± 0.11
channel 2H	53.68 ± 0.09	43.65 ± 0.08	10.03 ± 0.12
channel 3H	52.98 ± 0.07	42.89 ± 0.09	10.09 ± 0.11

The three experimental values are consistent.

They give an average weighted value of:

$$B_m^2 = 10.00 \ m^{-2} \pm 0.10$$

IV.3. Interpretation of the results

IV.3.1. Determination of the multiplication factors from the worth of the unit cell

The multiplication factors k_∞, k^* and k^+ of the test zones can be determined from the measured worth of the unit cell.

The starting point is the neutron balance equation in the fundamental mode, with leakage

$$(P - A)\Phi = DB^2\Phi$$

where P is the operator for neutron production, A for absorption and slowing down, D is the diffusion coefficient, and $\Phi(E)$ is the flux spectrum. Then, the factors k^* and k^+ are defined as follows

$$k^* = \frac{(1,\ P\Phi)}{(1,\ A\Phi)} \quad , \qquad k^+ = \frac{(\Phi^+,\ P\Phi)}{(\Phi^+,\ A\Phi)}$$

where $\Phi^+(E)$ is the fundamental adjoint spectrum.

The "infinite lattice" or "static mode" flux spectrum Φ_∞ is defined from the balance equation without leakage

$$\left(\frac{P}{k_\infty} - A\right)\Phi_\infty = 0$$

from which one obtains the multiplication factor

$$k_\infty = \frac{(1, P\Phi_\infty)}{(1, A\Phi_\infty)}$$

All three multiplication factors can be derived from the measured worth of the unit cell, using a relation of the type

$$k = 1 + m \frac{\delta k_{cell}}{\delta k_{U5}} + \varepsilon \qquad (4\text{-}1)$$

with calculated coefficients m and ε.

The experimental determinations of the different multiplication factors is in three respects interesting:

1) k^+ is determined directly from the cell worth measurements. It is the result of the "$k_\infty = 1$" experiment.

2) k^* allows to obtain an analysis of the neutron balance in the cell, using reaction rate measurements.

3) k_∞, calculated value without leakage, permits a comparison with other laboratories.

Note also that k^+ and k_∞ values, in this range of enrichment are practically identical.

All the details of m and ε calculations are given in Appendix II. Only the main points are discussed here:

- SNEAK-8 and 8Z: the calculations were performed with one-dimensional diffusion theory in spherical geometry, with the MOXTOT cross section set.

- UK 1 and UK 5 ERMINE: the calculations were performed with one-dimensional transport theory in cylindrical geometry, with the Cadarache version II cross section set.

The calculated coefficients are the following:

	UK 1		SNEAK-8		SNEAK-8Z		UK 5	
	m	ε	m	ε	m	ε	m	ε
k_∞	0.43	0.0001	0.45	0.0002	0.46	-0.0002	0.46	0.0010
k^+	0.43	0.0001	0.45	0.0002	0.46	-0.0002	0.46	0.0010
k^*	0.57	0.0001	0.57	0.0002	0.57	-0.0002	0.60	0.0013

The tests performed on the calculational method of m and ε led to the following accuracies:

$\pm$ 5 % for m

$\pm$ 0.001 for ε

IV.3.2. Determination of k^+ and k^* from buckling measurements

The multiplication factors k^+ and k^* were obtained from the material buckling measurements using the calculated value of the migration area M^{+2} and M^{*2}. The calculations were performed in fundamental mode.

The balance equation is

$$(P - A)\,\Phi = DB^2\Phi$$

the notation is defined on page 26.

One obtains thus:

$$M^{+2} = \frac{(\Phi^+, D\Phi)}{(\Phi^+, A\Phi)} \qquad M^{*2} = \frac{(1, D\Phi)}{(1, A\Phi)} \tag{4-2}$$

with $k^+ = 1 + M^{+2}\,B^2$ and $k^* = 1 + M^{*2}\,B^2$.

For UK 5, the Cadarache version II set gives the following results:

$$M^{+2} = 63.0\ cm^2 \qquad M^{*2} = 81.0\ cm^2$$

The accuracy on the M^2 values was assumed to be $\pm 5\%$.

IV.3.3. Results

The experimental values of the three multiplication factors, obtained from the five assemblies using the Eqs. (4-1) and (4-2) are given in the following table.

	UK 1 ERMINE	SNEAK-8	SNEAK-8Z	UK 5 ERMINE	UK 5 HARMONIE
k^+	0.9970±.0026	1.0065±.0018	1.0185±.0020	1.0645±.0037	1.0630±.0035
k_∞	0.9970±.0026	1.0065±.0018	1.0185±.0020	1.0645±.0037	
k^*	0.9970±.0026	1.0085±.0018	1.0220±.0020	1.0840±.0045	1.0810±.0050

The error contributions to the k-measurements are listed in Table IV-5.

V. SPECTRAL INDEX MEASUREMENTS

V.1. SNEAK

The fission ratios σ_{f8}/σ_{f5} and σ_{f9}/σ_{f5} were measured with activation foils in the central cell of the test zone. The measurements were normalized to foils irradiated between calibrated parallel plate fission chambers in position 17/17, which is far enough from the center that the central spectrum is not influenced by the presence of the chamber. The ^{238}U fission chamber was calibrated relative to the ^{235}U chamber by comparison of the fission rates with a natural uranium chamber in a fast and a thermal neutron flux. The ^{239}Pu chamber was calibrated against the ^{235}U chamber in a thermal flux, assuming the ratio of the thermal cross sections to be known. The spectral index σ_{c8}/σ_{f5} was determined from absolute reaction rate measurements with activation foils. The ^{238}U capture rate was obtained from the γ-activity of the 270 keV line measured with a Ge(Li)-detector, which was calibrated using an ^{243}Am foil of known intensity. For the absolute fission rate determination,the effective mass of a ^{235}U chamber was determined using exact chemical weighing procedures and cross-calibrations to ^{233}U chambers which were calibrated by low geometry α-counting /16/.

The fission spectral indices in the central cell were first determined at an arbitrarily selected reference position between two U_{nat} platelets (Fig. V-1 and V-2). These measurements were at least once repeated to check the reproducibility.

The fine structure of the fission rates within the unit cell was measured with foils, which were irradiated at 6 positions in the cell. One was at the center of the enriched uranium platelet, using a platelet with a central hole. The other positions were between normal platelets.

Only the fission rate of ^{238}U shows a noticeable fine structure. It is shown for SNEAK-8 and 8Z in Fig. V-1 and V-2. In SNEAK-8, the fine structure was also measured by the Cadarache group; the values are included in Fig. V-1. Calculated distributions are also shown; they were obtained with the KAPER program with both the MOXTOT and the KFKINR set. For the other fission rates, and also for the capture rate in ^{238}U, the variation within the cell is negligibly small.

The shape of $\sigma_{f8}\Phi$ calculated with MOXTOT shows larger variations than the one with KFKINR. The reason is that KFKINR has a reduced inelastic scattering cross section of ^{238}U. The measured points follow in principle the calculated shape; they are in between the MOXTOT calculation and the KFKINR calculation. The point in the enriched U plate in SNEAK-8 is not compatible with the calculated shape; probably the measurement is in error.

The cell-averaged fission rates $\sigma_{f8}\Phi$, normalized to the reference point, were obtained by interpolation between the measured points, using the calculated shape. The factors are given in Table V-1. For σ_{f9}/σ_{f5}, the factor is one, as there is no fine structure.

Besides the axial fine structure, there is also a non-negligible decrease of the fission rate $\sigma_{f8}\Phi$ across the platelet in the direction towards the edge. This decrease is due to the strong inelastic degradation of neutrons above the fission threshold by the stainless steel tube. The distributions across the platelets were found by foil measurements at the edges and at the corners of the platelets, normalized to the plate center. A correction factor of 0.99 for σ_{f8}/σ_{f5} was found both for SNEAK-8 and 8Z. With these corrections, one obtains the cell-averaged fission ratios for the center of the assemblies, as quoted in Table V-1.

The cell-averaged fission ratios in SNEAK-8 were also measured by the Cadarache group. The foils were irradiated in SNEAK, and counted in

Cadarache. These measurements were normalized to the parallel plate fission chambers of GfK. The results are also quoted in Table V-1. They agree well with the GfK measurements.

The spectral index σ_{c8}/σ_{f5} is available only for SNEAK-8. The value, obtained as an average over several foil measurements, is

$$\sigma_{c8}/\sigma_{f5} = 0.115 \pm 0.002$$

The Cadarache group measured also σ_{c8}/σ_{f5} in SNEAK-8. The measurement was completely independent because it was normalized to the value in the thermal column of the reactor HARMONIE in Cadarache. The result is

$$\sigma_{c8}/\sigma_{f5} = 0.118 \pm 0.002$$

The two results are consistent within the combined standard deviations.

For easier comparison with other assemblies, and with calculated values, the spectral indices were corrected to the fundamental mode (FM) neutron spectrum, and also to the static neutron spectrum (see Section IV.3.1.). The correction factor for a spectral index I is of the form

$$\frac{I \text{ (static)}}{I \text{ (assembly)}} = 1 + m_I \frac{\delta k_{cell}}{\delta k_{U5}} + \varepsilon_I,$$

where I (assembly) is the index in the complete assembly, and I (static) is the index in the static spectrum. Obviously, ε_I corrects to the FM spectrum, and $m_I \, \delta k_{cell}/\delta k_{U5}$ corrects from FM to the static spectrum.

The calculated coefficients are

	SNEAK-8		SNEAK-8Z	
	m_I	ε_I	m_I	ε_I
σ_{f8}/σ_{f5}	-0.49	-0.002	-0.50	-0.0020
σ_{f9}/σ_{f5}	0.04	0.0015	0.05	0.0010
σ_{c8}/σ_{f5}	-0.03	-0.002	-0.05	-0.0015

The corrections ε_I are generally small. The corrections to the static spectrum are small, except for σ_{f8}/σ_{f5} in SNEAK-8Z. The corrected values are also quoted in Tables V-1 and V-2.

V.2. ERMINE

V.2.1. Fission ratios

The fission ratios σ_{f8}/σ_{f5} and σ_{f9}/σ_{f5} were measured with cylindrical or parallel plate fission chambers in the depleted uranium. The parallel plate fission chambers replaced one square rod (12.7 x 12.7 mm^2) of depleted uranium. For the measurements with the cylindrical chambers, 3 or 4 rods, Ø 6.35 mm of depleted uranium replaced one square rod in the central cell.

Chamber positions for these measurements are shown in Fig. V-3.

V.2.2. Capture measurements σ_{c8}/σ_{f5}

The ^{238}U capture rate was determined using activation foils of 0.04% depleted uranium. The γ-activity of the ^{239}U at 74 keV was measured with a Ge(Li)-spectrometer.

In order to obtain the ^{235}U fission rate, a parallel plate fission chamber was placed in the reference channel. The ^{235}U fission rate in the fuel was then determined from chamber measurements and the ratio of activation of ^{235}U foils between the fuel and the chamber position /15/.

V.2.3. Heterogeneity measurements

The heterogeneity of the reaction rates in the cell was obtained from measurements of the average rates in the enriched uranium, relative to the average rates in the depleted uranium.

Foils of 12.7 mm diameter and 0.2 mm thickness were used; a 0.04% depleted uranium foil for capture ^{238}U, a 0.43% depleted foil for fission ^{238}U and a 93% enriched uranium foil for fission ^{235}U.

The foil positions are shown in Fig. V-3.

V.2.4. Corrections

a) Heterogeneity measurements: The experimental results were corrected, using the cell code HETAIRE, for the dilution and flux perturbations introduced by the foils.

b) Spectral indices:

- fission rates: Calculated corrections were applied to convert the measured values from the fission chamber position to mean values in the depleted uranium. (This correction depends, of course, on the position and the geometry of the chamber.) The fine structure in the depleted uranium was obtained using a fine cell calculation in the fundamental mode. The flux in the center of the test zone was not exactly the fundamental mode spectrum; a correction for the spectral mismatch was applied.

- capture ratios: two corrections were applied: one for the foil perturbations, the other for the spectral mismatch.

c) Results: cell average fission ratios: The cell average fission ratios were obtained from the fission chamber and heterogeneity measurements, using the following relation:

$$\left(\frac{\sigma_x}{\sigma_{f5}}\right) = \left(\frac{\sigma_x}{\sigma_{f5}}\right)_D \cdot \frac{N_x^D V^D + N_x^E V^E \cdot \left(\frac{\sigma_x^E \Phi^E}{\sigma_x^D \Phi^D}\right)}{N_5^D V^D + N_5^E V^E \cdot \left(\frac{\sigma_{f5}^E \Phi^E}{\sigma_{f5}^D \Phi^D}\right)} \cdot \frac{N_5^D V^D + N_5^E V^E}{N_x^D V^D + N_x^E V^E}$$

where $\left(\frac{\sigma_x}{\sigma_{f5}}\right)_D$ is the reaction rate ratio measured in the depleted uranium

D = depleted uranium

E = 30% enriched uranium

V^i = volume of the region i

N_x^i = atom density per cm^3 of isotope x in region i

With regard to ^{239}Pu, it was assumed that N_9^i was a constant in the cell.

The results and the applied corrections (measured and calculated) are given in Table V-3 and V-4.

V.3. HARMONIE

V.3.1. Heterogeneous fission measurements for ^{235}U and ^{238}U

Relative fission reaction rate measurements were performed for ^{235}U and ^{238}U using 93% enriched and 0.43% depleted uranium foils. These were placed (see Fig. V-4):

a) Close to the center of the assembly, at 45.7 cm and 40.6 cm from the base:

- between 30% enriched uranium rods (9 positions)
- between depleted uranium rods (5 positions)

b) In dummy fission chambers, placed at the periphery of the assembly (reference position).

Two fission chambers (parallel plate chambers) were jointly positioned at the same place as the dummy chambers, in order to obtain the absolute value of the fission ratio σ_{f8}/σ_{f5} in the reference position and to normalize the results.

V.3.2. Capture measurements: σ_{c8}/σ_{f5}

The capture measurements were performed using enriched and depleted uranium foils, similar to those used for the fission measurements.

The ^{238}U capture rates were determined by counting the ^{239}Np activity induced in 0.43% depleted uranium foils, with a detection window set at 75 - 135 keV.

The ^{235}U fission rates were obtained by counting the activity induced in 93% enriched uranium foils above 511 keV.

The σ_{c8}/σ_{f5} value was related to those in a thermal spectrum, using simultaneous foil irradiations in the test region and in a thermal column /15/.

V.3.3. Corrections

Four corrections are required to obtain the experimental values of the reaction rate ratios in the fundamental mode /17/:

a) Correction for the tube:

In principle, one would have to correct the experiments to the case where the tube is homogenized, in order to have a good comparison with calculations. However, this effect is negligible in the present core.

b) Correction for the dilution effects:

To take into account the difference between the dilutions of chamber and foils, on one hand, and between fuel and foils on the other hand.

c) Correction for the axial curvature:

To get, from the measured rates at different heights, the rates corresponding to the same point on the axis.

d) Correction for the presence of harmonics:

To obtain the experimental values in the fundamental mode.

V.3.4. Results

Using all the corrected reaction rate measurements (9 + 5 positions), one can obtain the average rate for the reaction x relative to the rate in a reference position, in the 30% enriched uranium (R_x) and in the depleted uranium (r_x) in the fundamental mode. The "cell average" reaction rates for the reaction x are thus:

$$\overline{R_x} = \frac{N_x R_x + 3 r_x n_x}{N_x + 3 n_x}$$

where the atom density of isotope x is N_x in 30% enriched uranium and n_x in depleted uranium.

The final values of the experimental reaction rate ratios are then:

$$Ix/_5 = \left(\frac{\sigma_x}{\sigma_{f5}}\right)_{Ref} \cdot \frac{\overline{R_x}}{\overline{R_5}}$$

Ref = fission chamber (σ_{f8}/σ_{f5}) or thermal (σ_{c8}/σ_{f5}) values.

The results are given in Table V-5.

V.4. Summary of the results

The experimental "cell average" values of the reaction rate ratios, in the fundamental mode, are given for the five assemblies in the following table.

Core	UK 1 ERMINE	SNEAK-8	SNEAK-8Z	UK 5 ERMINE	UK 5 HARMONIE
σ_{f8}/σ_{f5}	0.0220±.00022	0.0224±.0004 0.0226±.0004*	0.0227±.0004	0.0243±.00025	0.0244±.00025
σ_{f9}/σ_{f5}	1.095 ±.011	1.094±.020	--	1.105 ±.011	--
σ_{c8}/σ_{f5}	0.117±.0015	0.115±.002 0.118±.0015*	--	0.116±.0015	0.119 ±.0015

*) Measurements performed in SNEAK by the Cadarache group.

VI. SPECTRUM MEASUREMENTS

VI.1. SNEAK

The spectrum in the center of SNEAK-8 was measured with proton recoil counters between 35 keV and 1.5 MeV. Several spherical counters with different fillings of hydrogen or methane were used to cover this energy range. (n,γ) discrimination was applied at energies below 100 keV. The reactor was critical, but at low power, in the order of a few milliwatts. Furthermore, the spectrum between 100 keV and 2.5 MeV was measured with ^{3}He sandwich spectrometers, which contained two Si semiconductor surface barrier detectors, and a proportional counter which uses the space between the detectors as active volume. A detailed description is given elsewhere /18/.

For easier comparison, the measured spectra were normalized to a calculation in 208 energy groups. The results are presented and discussed in Section VII.2.3.

VI.2. ERMINE and HARMONIE

Measurements of the neutron spectrum were performed using proton recoil counters /19/. The cylindrical counters (25 mm in diameter, 75 mm in length), were placed as closely as possible to the vertical axis of the assemblies. The positions in ERMINE and HARMONIE were consistent. The arrangement in the both assemblies are given in Fig. VI-1. The spectrum was measured between 10 keV and 1.4 MeV using three counters with different fillings and pressures but with the same geometry. In any case the arrangement of the counters was identical in order to obtain a very good reproducibility.

The detailed descriptions of the electronic apparatus are given in /19/. The experimental results are presented in Section VII.2.3., for comparison with calculations.

VII. ANALYSIS AND COMPARISON WITH CALCULATIONS

VII.1. Calculated Results

VII.1.1. Cell parameters

The cell parameters k_∞, k^*, and B^2 for the four compositions were calculated at GfK, using the cross section sets MOXTOT and KFKINR, and at CEA, using the Cadarache cross section set Version II. At CEA, k^+ and M^2 for UK 1 and UK 5 were also calculated. The results are given in Table VII-1.

VII.1.2. Spectral indices

The spectral indices were also calculated at GfK and CEA. The results for the fundamental mode are shown in Table VII-2, for the static mode ($B^2 = 0$) in Table VII-3. The ratio σ_{cSt}/σ_{f5} of capture per atom of structural material to fission in ^{235}U is also included.

VII.1.3. Reactivity worths

The calculated reactivity worths of ^{238}U, SS and Ni normalized to the worth of ^{235}U, are shown in Table VII-4.

VII.2. Comparison of calculation and experiment[+)]

VII.2.1. Multiplication factors k_∞ and k^*

The measured multiplication factors for the four cores are listed in Table VII-5, and compared with calculations performed at GfK and CEA. The experimental results of SNEAK-8, 8Z, and UK 5 are well consistent, whereas one would expect a value which is about 0.7% higher for UK 1. The reason for this difference, which corresponds to slightly more than two standard deviations, is not known.

Whereas the GfK calculations with MOXTOT are too low by two percent or more, KFKINR gives results which are within 1% of the experimental values, and can thus be considered acceptable. This considerable improvement is mainly due to the changes in the inelastic scattering of ^{238}U.

The two Cadarache cross section sets give both very good results for the multiplication factors.

+) Note that all errors of experiments quoted in this report correspond to a one σ confidence interval.

VII.2.2. Spectral indices

The fission ratio σ_{f8}/σ_{f5} is the only spectral index for which the static mode value is significantly different from the fundamental mode value. Therefore, the comparison between measurement and calculation (Table VII-6) is carried out in both modes.

In brief, in the static mode, the calculated and experimental values are compared for the same buckling - which is $B^2 = 0$ - but with a calculated eigenvalue, k_{eff}, which may be different from one. This method is generally used at GfK. In the fundamental mode, the comparison is for $k_{eff} = 1$, but with a calculated B^2 that may be different from the experimental one. This method is preferred at CEA because it may be used for lattices where k_∞ is substantially different from one.

The measured fission ratios σ_{f8}/σ_{f5} are well consistent between the five cores. The calculations with MOXTOT largely underestimate σ_{f8}/σ_{f5}, but KFKINR gives good results. This difference indicates again that the modifications in σ_{in_8} have brought significant improvement.

The Cadarache sets also give good agreement. Version III is slightly better, but the difference is very small.

The fission ratios σ_{f9}/σ_{f5} were again measured with consistent results. Thus, it has been demonstrated that the techniques and calibrations used to measure fission ratios at GfK and CEA give results which are well in agreement. The calculations are satisfactory except MOXTOT.

The measurements of the index σ_{c8}/σ_{f5} show much larger fluctuations than the fission ratios. The ERMINE values are in good agreement, the GfK measurement in SNEAK-8 is 2.5% lower, the HARMONIE measurement is about 2.5% higher. These differences can only be stated, but not explained in the context of this report. Also, the calculated results between all the sets involved are different. With respect to the mean experimental value, MOXTOT and Cadarache version III give good results, while KFKINR is slightly high and Cadarache II is somewhat low.

VII.2.3. Neutron spectrum

a) Comparison between the different experimental results

The fine spectra measured in the center of SNEAK-8, UK 5 HARMONIE and UK 5 ERMINE with the proton recoil counters are compared in Fig. VII-1.

The fine spectra do not show systematic discrepancies. The differences, at the error limits, between ERMINE and HARMONIE are due to the spectrum mismatch caused by the driver zone in ERMINE. Subsequently we will use for UK 5 the HARMONIE spectrum only, closer to the fundamental mode.

b) Comparison between experiment and GfK calculations

Fig. VII-2 shows the ratio of measured to calculated spectra in SNEAK-8, for both the proton recoil measurements, and the ^{3}He spectrometer meas-

urements. The calculation was performed in 208 groups with data from the Karlsruhe Nuclear Data File KEDAK. The inelastic scattering data for ^{238}U on KEDAK are similar to those in the MOXTOT set. A similar comparison of measured and calculated spectrum for UK 5 HARMONIE is shown in Fig. VII-3.

The main feature of these comparisons is that the spectrum is strongly underpredicted around 1.6 MeV, and overpredicted between 30 and 60 keV. These discrepancies strongly suggest that both the inelastic scattering cross section around 1.6 MeV, and the capture cross section of ^{238}U at 40 keV on KEDAK are too large. Similar results were obtained from experiments which were performed in Karlsruhe on a depleted uranium block /18/. In Ref. /18/, the inelastic scattering cross section of ^{238}U was adjusted to fit the experimental data. It should be mentioned that the use of these adjusted data greatly improves the calculated spectrum for SNEAK-8, and that the adjusted cross sections are consistent with the data on which the KFKINR set is based.

c) Comparison between experiment and CEA calculations

For this comparison a 25 group calculation is used. The experimental multigroup spectrum is the result of the condensation of the fine spectrum. The deviations $\frac{C-E}{C}$ with the version III Cadarache set are given for UK 5 HARMONIE and SNEAK-8 in Table VII-7. Measurement and calculation are normalized over the range 15 to 1350 keV for UK 5, 40.9 to 1350 keV for SNEAK-8. The calculations show discrepancies with the measurement of about 20%. As mentioned above, the calculated spectrum is very sensitive to the inelastic cross section data set of ^{238}U.

VII.3. Balance of reaction rates

The neutron balance in the fundamental mode was set up for UK 1, UK 5, and SNEAK-8. The balance is written as a comparison between k^* obtained from the cell worth or buckling measurements, and k^* obtained from the measured spectral indices, plus ν_5, α_5 and ν_8 as calculated from differential data. The calculated values from the KFKINR set and the Cadarache set (version II) were used. The results are given in Tables VII-8 and VII-9. Only experimental errors are considered in these tables.

An examination of the tables in Section VII.2. shows that the measured parameters σ_{f8}/σ_{f5} agree well between the various lattices. It is the same with k^* except in UK 1 where the measured value seems to be too low.

The large variations observed on the deviation between k^* obtained by the reactivity method and k^* obtained from the measured spectral indices, for the different cores come mainly from the large dispersion of measured σ_{c8}/σ_{f5}.

The neutron balance allows to check the consistency of the measured σ_{c8}/σ_{f5} ratios with the calculated ν and α values from the two cross section sets. Note that the ν and α from the KFKINR set are more reactive (high ν_5, low α_5) than those from the Cadarache version II set.

Then one finds from the results in Tables VII-8 and VII-9 that all the different capture measurements are consistent with the data from the highly reactive KFKINR set, the difference being about one standard deviation for the SNEAK-8 and the HARMONIE UK 5 measurements, and practically zero for ERMINE UK 5.

On the other hand, the Cadarache version II set is certainly under-reactive, because it is not consistent with the measurements.

From the study of the neutron balance one may obtain experimental values of α_5 although the accuracy is not good (indeed one percent of error on ν_5 leads to 8 percent on α_5 and one percent on σ_{c8}/σ_{f5} leads to about 7 percent on α_5). The results are shown in the following table.

	UK 1 ERMINE	SNEAK-8	UK 5 ERMINE	UK 5 HARMONIE
KFKINR	0.238	0.260 0.214+)	0.200	0.173
Cadarache version II	0.196	0.215 0.167+)	0.164	0.134

+) Using σ_{c8}/σ_{f5} measured by the Cadarache group.

VIII. EXTRAPOLATION TO THE CASE OF MINIMUM ENRICHMENT

In order to have a common representation, the parameters of a pure uranium homogeneous lattice with k-infinity exactly equal to unity were obtained by extrapolation of the experimental results from the five cores: enrichment, reaction rate ratios. In order to eliminate errors due to the method, two different extrapolation methods were employed. The influence of the cross section set was also tested. All the results are given with one σ confidence interval.

VIII.1. ρ_8/ρ_5 and < C/E > method

It was found by calculation that the ratio ρ_8/ρ_5 of the reactivity worth per gram of ^{238}U to the worth of ^{235}U is the same, within less than 0.1%, for the homogeneous compositions of UK 1, SNEAK-8, SNEAK-8Z, and a pure uranium composition with $k_\infty = 1$. Only UK 5, with its rather high enrichment, has a ρ_8/ρ_5 which is 0.28% smaller. This ratio is also insensitive to the spectrum mismatch.

Therefore ρ_8/ρ_5 was determined from the reactivity measurements of the core materials, for each core separately. Corrections for the can or nickel coating, for the impurities in the uranium metal, and for enrichment (UK 5) were applied, and the results were converted by calculation to the homogeneous case. One then obtains a corrected ratio $\delta k_U/\delta k_5$, from which ρ_8/ρ_5 can be derived using the equation

$$\frac{\rho_8}{\rho_5} = \frac{m_5}{m_8}\left[\frac{\delta k_U}{\delta k_5} - 1\right]$$

Note that δk_U is the reactivity worth of the uranium in the cell and m_5, m_8 are the ^{235}U and ^{238}U masses in the cell. The minimum enrichment $E = N_5/(N_5+N_8)$, where the N are atom densities, is then simply obtained for the homogeneous medium with $k_\infty = 1$, by the equation

$$1 + \frac{N_8}{N_5} \frac{A_8}{A_5} \frac{\rho_8}{\rho_5} = 0$$

where A_8 and A_5 are the atomic mass numbers of ^{238}U and ^{235}U.

The results obtained using the KFKINR data set for the corrections, are given in Table VIII-1. The error contributions to ρ_8/ρ_5 for each assembly are summarized also in this table. Note that an additional error of 0.5% was added, to account for the uncertainty in the conversion to the pure uranium core.

The minimum enrichment, average value of the four experiments, is thus 5.56%.

The spectral indices for this composition are obtained by applying the mean value $< C/E >$ of the ratio of calculation and experiment. The C/E-values are gathered in Table VIII-2, using the KFKINR data set.

The experimental reaction rate ratios, obtained by applying the mean value, are the following, for the minimum enrichment 5.56%

$$\sigma_{f8}/\sigma_{f5} = 0.02273 \pm .0002$$

$$\sigma_{f9}/\sigma_{f5} = 1.097 \pm .008$$

$$\sigma_{c8}/\sigma_{f5} = 0.1166 \pm .0017$$

VIII.2. Regression method

The experimental results are reduced by calculations to the case of homogeneous compositions with a content of structural material that is an average between the SNEAK-cores and the UK-cores, and with an average uranium density (d = 16.5 g/cm^3). The average structure was defined in terms of the relative atom densities of Fe, Cr and Ni

$$\frac{N_{Fe}}{N_U} = 0.087 \qquad \frac{N_{Cr}}{N_U} = 0.025 \qquad \frac{N_{Ni}}{N_U} = 0.037 \ .$$

The corrections are very small ($\leq$ 0.25% in k-infinity).

The minimum enrichment and the spectral indices, for the $k_\infty = 1$ medium with structure, are obtained by extrapolation using least square adjustment versus enrichment. In fact, the relation between k^+ and E is not linear for UK 5. An additional correction (0.2% in k_∞) was added by calculation before adjustment. The results of the least square adjustment are given in Fig. VIII-1, using the Cadarache sets for the corrections.

These results are corrected by calculations in order to obtain the parameters for the pure uranium medium with $k_\infty = 1$. We obtain thus:

$$E = 5.56\% \pm 0.02$$

$$\sigma_{f8}/\sigma_{f5} = 0.02270 \pm 0.0002$$

$$\sigma_{f9}/\sigma_{f5} = 1.109 \pm 0.008$$

In view of the dispersion of the experimental results, it is not possible to use the regression method for the capture measurements. Only the < C/E > method was applied. We obtain thus using the version III Cadarache set:

$$\sigma_{c8}/\sigma_{f5} = 0.1166 \pm 0.0017$$

VIII.3. Influence of the cross section set

The influence of the cross section sets and also of the extrapolation methods was tested using the Cadarache cross section set. The results are compared in the following table.

Cross section Set	KFKINR	Cadarache	Cadarache
Method	ρ_8/ρ_5	ρ_8/ρ_5	regression
E	5.56 ± 0.02	5.54 ± 0.02	5.56 ± 0.02
σ_{f8}/σ_{f5}	0.02273 ± 0.0002	0.02273 ± 0.0002	0.02270 ± 0.0002
σ_{f9}/σ_{f5}	1.097 ± 0.008	1.107 ± 0.008	1.109 ± 0.008
σ_{c8}/σ_{f5} +)	0.1166 ± 0.0017	0.1166 ± 0.0017	0.1166 ± 0.0017

+) obtained from the C/E ratio

VIII.4. Experimental pure uranium composition with $k_\infty = 1$

All the results, obtained using different methods and cross section sets for the corrections, are consistent within the error limits. We can thus define the standard homogeneous core in pure uranium with $k_\infty = 1$, by taking the average between the values obtained in the two laboratories. The enrichment and the reaction rate ratios are given in the following table with one σ confidence interval.

Standard uranium composition with $k_\infty = 1$

E (a/o)	5.56 ± 0.02
k_∞	1.000
σ_{f8}/σ_{f5}	0.02272 ± 0.00020
σ_{f9}/σ_{f5}	1.103 ± 0.008
σ_{c8}/σ_{f5}	0.1166 ± 0.0017

It should be mentioned that the parameters for a similar standard uranium composition, called "SCHERZO 556", were derived from the cores described in this report, plus the assembly ZEBRA-8H. The results, quoted from reference /2/, are: E = (5.56 ± 0.02) %, σ_{f8}/σ_{f5} = 0.0227 ± 0.0002, σ_{c8}/σ_{f5} = 0.1154 ± 0.0017. Both standards agree within the error limits.

VIII.5. Comparison with calculation

VIII.5.1. Calculated results

The calculated parameters for this composition, obtained with the cross section sets KFKINR and Cadarache version III, are given in Table VIII-3.

VIII.5.2. Comparison of experimental and calculated parameters

The calculations are compared with the experimental results in the following table.

Comparison of experiment and calculation

$(\frac{C-E}{C})$ in %	KFKINR	Cadarache version III
k_∞	- 0.6	- 0.13
σ_{f8}/σ_{f5}	+ 0.8	+ 1.5
σ_{f9}/σ_{f5}	+ 1.9	+ 0.2
σ_{c8}/σ_{f5}	+ 2.4	+ 0.5

The two cross section sets give both good results; the differences are close to the error limits. We can mention three points, as in Section VII:

- KFKINR gives a multiplication factor k_∞ too low by 0.6%
- Cadarache version III overestimates slightly the fission ratio σ_{f8}/σ_{f5}
- KFKINR is slightly high for the capture ^{238}U.

VIII.6. Neutron balance

It is interesting to determine k^* for the standard uranium composition from the spectral indices, and the values $\nu_5 = 2.480$, $\nu_8 = 2.844$, and $\alpha_5 = 0.206$ from the KFKINR set. One obtains $k^* = 1.005 \pm 0.010$, which is consistent with $k^* = 1$. On the other hand, if one solves the balance equation for α_5, one obtains $\alpha_5 = 0.225 \pm 0.035$.

In the same way, using the calculated values from the version III Cadarache set, one obtains $k^* = 0.998 \pm 0.010$ and $\alpha_5 = 0.238 \pm 0.035$. Both values are consistent, first with the direct value of k^*, second with the calculated value α_5 from version III Cadarache set. Thus, the ν and α values of both the KFKINR set and version III Cadarache set are consistent with the parameters of the standard uranium composition, though only within fairly large error limits.

CONCLUSIONS

Since 1969 a close cooperation in the physics of fast neutron reactors has been pursued between the laboratories of Karlsruhe (IASR-SNEAK), the laboratories of Cadarache (DPRMA-SECPR) and Fontenay-aux-Roses (DPRMA-SPE).

Within the frame of this cooperation, similar studies on lattices in metallic uranium with unit k_∞ (which were proposed as standard lattices for international comparison) were carried out in the two countries, and are jointly reported in this paper.

The studies were performed in a fast critical assembly (SNEAK), in a fast-thermal critical assembly (ERMINE), and in an exponential experiment (HARMONIE). Four lattices were built: SNEAK-8 and 8Z, UK 1 and UK 5.

Experimental techniques

These studies allowed to compare the experimental techniques used at the different laboratories to obtain the k-infinity of the lattices (determination from the worth of the unit cell or from the buckling measurement), the various spectral indices σ_{f8}/σ_{f5}, σ_{f9}/σ_{f5} and σ_{c8}/σ_{f5} and the spectrum with proton recoil counters.

Particular care was taken in assigning accuracies to the measured values and to extensively review the various uncertainties.

Analysis

Several methods have been used for the analysis, and a comparison of the results allowed to check the validity of these methods. A comparison of the calculated values obtained with the cross section sets used in the two countries (MOXTOT, KFKINR, Cadarache version II and III) was also performed.

Results

k-infinity

The measured values are well consistent except perhaps the UK 1 value which seems low by about two standard deviations. The calculated values with the two Cadarache sets are good. The values with the MOXTOT set are too low by about two percent. The KFKINR set gives results which deviate from measured values less than one percent and can be considered as acceptable.

Reaction rate ratios

The measured ratios σ_{f8}/σ_{f5} and σ_{f9}/σ_{f5} are in good agreement and the deviations between measured and calculated values are satisfactory except for the MOXTOT set.

The measurements of σ_{c8}/σ_{f5}, on the other hand, do not seem to be consistent. The maximum discrepancy between the experimental values is about 5 percent, and no explanation has been found for this rather large dispersion.

Standard core

From these measurements, the characteristics of a standard core with k_∞ equal to one were deduced.

Three different extrapolation methods were used, and the results are well consistent.

The mean values are given in the following table with one σ confidence interval.

E	5.56% ± 0.02
k_∞	1.000
σ_{f8}/σ_{f5}	0.02272 ± 0.00020
σ_{c8}/σ_{f5}	0.1166 ± 0.0017

Because of the fairly large uncertainly of the ^{238}U capture rate, not much information can be obtained from the detailed neutron balance.

Nevertheless, if one accepts the mean value for σ_{c8}/σ_{f5}, one can draw the conclusion that the neutron balance is consistent if ν_5, α_5, and ν_8 from either the KFKINR set, or the version III Cadarache set are used.

The values for the standard core can be checked, and perhaps improved, by an intercomparison with results from similar lattices studied in other countries, e.g. Japan, and U.S.A. Thus, a comparison with the results obtained from ZEBRA-8H has been performed, and published in Ref. /2/. Also, a preliminary comparison with assembly FCA-IV-1 in Japan (for k_∞ and σ_{f8}/σ_{f5}) seems to indicate that the results confirm the standard given in this paper.

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Table II-1 Data for the test cells

Core	UK 1 ERMINE	SNEAK-8	SNEAK-8Z	UK 5 ERMINE-HARMONIE
Enrichment $\frac{M5}{M5+M8}$	0.0574	0.05800	0.05961	0.0652
Mass U5 g/cm^3	0.910	0.9270	0.9530	1.034
Mass U8 g/cm^3	14.94	15.054	15.033	14.82
Mass SS g/cm^3	0.396	0.531	0.531	0.396
Mass Ni g/cm^3	0.119	0.071	0.071	0.125
$\frac{N5}{N5+N8}$	0.0581	0.05871	0.06033	0.0660
N5 (10^{20} at/cm^3)	23.31	23.754	24.420	26.48
N8 (10^{20} at/cm^3)	377.9	380.90	380.36	374.9
N Fe (10^{20} at/cm^3)	31.03	39.68	39.68	31.03
N Cr (10^{20} at/cm^3)	9.916	11.12	11.12	9.916
N Ni (10^{20} at/cm^3)	16.21	12.96[a)]	12.99[a)]	16.84
N C (10^{20} at/cm^3)	3.19	3.76	3.76	3.19
N Mn (10^{20} at/cm^3)	--	0.87	0.87	--
N Mo+Nb (10^{20} at/cm^3)	--	0.18	0.18	--
N Si (10^{20} at/cm^3)	--	0.45	0.45	--
N H (10^{20} at/cm^3)	--	0.18	0.18	--
N Cu (10^{20} at/cm^3)	0.30	--	--	0.30
N Al (10^{20} at/cm^3)	0.32	0.24	0.24	0.32

a) 5.72 are from the SS tube, the rest from the Ni coating of the U platelets

Table II-2 Atom densities of the SNEAK driver zone and blanket (10^{20} at/cm^3)

	Normal driver cell	Average over radial driver	Blanket
C	495.98	483.75	0.14
Cr	11.08	12.69	11.08
Fe	39.55	45.48	39.55
Mn	0.87	0.98	0.87
Mo	0.10	0.08	0.10
Nb	0.08	0.07	0.08
Ni	8.30	9.05	9.85
Si	0.45	0.52	0.45
^{235}U	52.14	50.83	1.62
^{238}U	95.54	93.15	399.40

Table II-3 Atom densities of the ERMINE zones (10^{20} at/cm^3)

Zone	U depleted	Stainless steel + graphite	Thermal zone	Reflector	Stainless steel	H_2O + Al
^{235}U	1.779	--	1.34	--	--	--
^{238}U	422.6	--	0.147	--	--	--
Fe	31.03	21.2	--	--	609.0	--
Cr	9.916	5.70	--	--	164.0	--
Ni	16.21	2.80	--	--	80.0	--
Al	0.32	--	235.0	40.63	--	120.4
O	--	--	196.0	10.0	--	268.0
C	3.19	799.0	--	770.0	--	536.0
H	--	--	392.0	20.0	--	--
Cu	0.30	--	--	--	--	--

Table IV-1 Results of cell worth measurements in SNEAK

	SNEAK-8		SNEAK-8Z	
	Standard core	Clean core		
Worth of a plate cell, 10^{-5} $				
4 subassemblies				
cells 1-3	55.0±2.0	53.6±2.0	cells 1-3	75.8±2.5
cells 1-6	54.6±1.3	53.4±1.8	cells 1-7	76.0±1.4
cells 1-9	55.0±0.8	53.9±0.8	cells 1-10	76.3±1.0
weighted mean	55.0±0.8	53.8±0.8		76.2±1.0
9 subassemblies				
cells 1-3	54.5±1.3		cells 1-3	73.0±1.3
cells 1-6	54.1±0.8		cells 1-7	73.9±0.8
cells 1-9	54.5±0.7		cells 1-10	74.3±0.8
weighted mean	54.5±0.7			74.0±0.8
Average	54.8±0.6	53.8±0.8		75.1±1.2
Worth of SS 10^{-5} $/g	-1.075±0.02	-1.045±0.02		-1.09±0.02
Worth of SS 10^{-5} $/cell	-39.8 ±0.8	-38.7 ±0.8		-34.8 ±0.7
Worth of ^{235}U 10^{-5} $/g	16.8±0.2	16.5±0.2		17.3 ±0.3
Worth of ^{235}U 10^{-5} $/cell	1084±15	1065±15		995±20
Worth of the core composition per cell 10^{-5} $	15.0 ±1.0	15.1 ±1.3		40.2 ±1.4
Worth of the core composition relative to ^{235}U	0.0138±0.0012	0.0142±.0013		0.0404±0.0018

The unit cell contains 64.54 g ^{235}U (SNEAK-8)

57.45 g ^{235}U (SNEAK-8Z)

Table IV-2 UK 1 ERMINE - cell worth measurements for three thermal zone configurations (Height of the cavity: 101.6 mm)

Configuration	1	2	3
$\frac{\delta k \text{ rods}}{\delta k\ ^{235}U}$	0.0809 ± .0010	0.0910 ± .0016	0.0703 ± .0009
Correction for the spacers $\frac{\delta k \text{ Al}}{\delta k\ ^{235}U}$	-0.0407 ± .0021	-0.0407 ± .0021	-0.0407 ± .0021
Correction for the flux gradient	-0.0166 ± .0025	-0.0267 ± .0040	-0.0092 ± .0014
$\frac{\delta k \text{ steel sheath}}{\delta k\ ^{235}U}$	-0.0286 ± .0015	-0.0286 ± .0015	-0.0286 ± .0015
$\frac{\delta k \text{ cell}}{\delta k\ ^{235}U}$	-0.0050 ± .0037	-0.0050 ± .0050	-0.0082 ± .0030
Average $\frac{\delta k \text{ cell}}{\delta k\ ^{235}U}$		-0.0066 ± .0030	
Estimated errors { cell composition		± .0035	
Estimated errors { impurities		± .0022	
Final result $\frac{\delta k \text{ cell}}{\delta k\ ^{235}U}$		-0.0066 ± .0056	

Table IV-3 UK 5 ERMINE - cell worth measurements for different size of cavity

Height of cavity (mm)	20	40	60	80	101.6
$\frac{\delta k \text{ rods}}{\delta k\ ^{235}U}$	.2425 ± .0031	.2311 ± .0020	.2232 ± .0017	.2136 ± .0015	.2143 ± .0017
Correction for cell composition	-.0059 ± .0011	-.0092 ± .0011	-.0074 ± .0011	-.0057 ± .0011	+.0002 ± .0011
Correction for the spacers $\frac{\delta k \text{ Al}}{\delta k\ ^{235}U}$	-.0629 ± .0032	-.0434 ± .0022	-.0377 ± .0019	-.0337 ± .0017	-.0321 ± .0016
Correction for flux gradient	-.0127 ± .0019	-.0125 ± .0019	-.0134 ± .0020	-.0131 ± .0020	-.0147 ± .0022
$\frac{\delta k \text{ steel sheath}}{\delta k\ ^{235}U}$	-.0256 ± .0013	-.0256 ± .0013	-.0256 ± .0013	-.0256 ± .0013	-.0256 ± .0013
$\frac{\delta k \text{ cell}}{\delta k\ ^{235}U}$	.1354 ± .0054	.1404 ± .0039	.1391 ± .0037	.1355 ± .0034	.1421 ± .0036
Average $\frac{\delta k \text{ cell}}{\delta k\ ^{235}U}$			0.1386 ± .0034		
Estimated error for impurities			± .0022		
Final results $\frac{\delta k \text{ cell}}{\delta k\ ^{235}U}$			0.1386 ± .0040		

Table IV-4 Results of cell worth measurements

Assembly	UK 1 ERMINE (configuration 3)	SNEAK-8	SNEAK-8Z	UK 5 ERMINE (E = 101.6 mm)
Worth of core material $\frac{\delta k\ CM}{\delta k\ U5}$ (rods or plates)	0.0703 ± .0009	0.0505 ± .0009	0.0754 ± .0018	0.2145 ± .0020
Correction for spacers	-0.0407 ± .0021	--	--	-0.0321 ± .0016
Corrected result	0.0296 ± .0023	0.0505 ± .0009	0.0754 ± .0018	0.1824 ± .0026
Worth of SS $\frac{\delta k\ SS}{\delta k\ U5}$	-0.0286 ± .0015	-0.0365 ± .0016	-0.0350 ± .0016	-0.0256 ± .0013
Worth of the core composition (unit cell) $\frac{\delta k\ cell}{\delta k\ U5}$	+0.0010 ± .0027	0.0140 ± .0019	0.0404 ± .0024	0.1568 ± .0029
Correction for flux gradient	-0.0092 ± .0014	0.0 ± .0005	0.0 ± .0005	-0.0147 ± .0022
Corrected worth of the unit cell	-0.0082 ± .0030	0.0140 ± .0020	0.0404 ± .0025	0.1421 ± .0036
Final results, adding the estimated errors for cell composition and impurities	-0.0082 ± .0056	0.0140 ± .0031	0.0404 ± .0033	0.1421 ± .0040

Table IV-5 Error contributions to k_∞-measurements

(% uncertainty in k)

Source of error	UK 1	SNEAK-8	SNEAK-8Z	UK 5
Core material measurement	0.04	0.04	0.08	0.07
Spacer measurement	0.09	-	-	0.09
Sheath measurement	0.07	0.07	0.07	0.07
Cell composition	0.15	0.05	0.05	0.05
Impurities[+)]	0.10	0.10	0.10	0.10
Flux asymmetry	0.06	0.02	0.02	0.10
m	0.02	0.03	0.09	0.30
ε	0.10	0.10	0.10	0.10
total (rms)	0.26	0.18	0.20	0.37

+) Note: This accounts for uncertainties in composition due to impurities (mainly C and H) present in the uranium.

Table V-1 Measured fission ratios in SNEAK

	SNEAK-8		SNEAK-8Z
	σ_{f8}/σ_{f5}	σ_{f9}/σ_{f5}	σ_{f8}/σ_{f5}
Spectral index at the reference point	0.0220 ± 0.0004	1.096 ± 0.020	0.0219 ± 0.0004
Axial cell average / reference point	1.028	1.000	1.047
Radial average, correction factor	0.99	1.000	0.99
Cell-averaged spectral index at the core center			
GfK	0.0224 ± 0.0004	1.096 ± 0.020	0.0227 ± 0.0004
Cadarache	0.0226 ± 0.0004	1.087 ± 0.020	--
Spectral index (GfK), corrected to			
a) fundamental mode	0.02235± 0.0004	1.094 ± 0.02	0.02265± 0.0004
b) static spectrum	0.02220± 0.0004	1.094 ± 0.02	0.02220± 0.0004

Table V-2 Measured ratio σ_{c8}/σ_{f5} in SNEAK-8

	GfK	Cadarache
Spectral index in the central cell corrected to		
a) fundamental mode	0.1150 ± 0.002	0.1180 ± 0.002
b) static spectrum	0.1152	0.1183

Table V-3 Fission ratio measurements in ERMINE

Assembly	UK 1		UK 5	
Fission ratio	σ_{f8}/σ_{f5}	σ_{f9}/σ_{f5}	σ_{f8}/σ_{f5}	σ_{f9}/σ_{f5}
Measurements in depleted uranium	0.0218 ± 0.00018	1.104 ± 0.009	0.0240 ± 0.00020	1.116 ± 0.009
Correction	0.988+)	0.997+)	0.994+)	1.001+)
Fission ratio in depleted uranium (fundamental mode)	0.0215 ± 0.00018	1.101 ± 0.009	0.0239 ± 0.00020	1.117 ± 0.009
Ratio ($\frac{\text{cell average value}}{\text{depleted uranium value}}$)	1.023+)	0.995+)	1.017 ± 0.005	0.989 ± 0.005
Cell average value of spectral indices in fundamental mode	0.0220 ± 0.00022	1.095 ± 0.0011	0.0243 ± 0.00025	1.105 ± 0.0011

+) Calculated factors

Table V-4 Capture ratio σ_{c8}/σ_{f5} ERMINE

Assembly	UK 1	UK 5
Measurements in depleted uranium	0.117 ± 0.0013	0.117 ± 0.0013
Correction	1.007+)	1.010+)
Spectral indices in depleted uranium (fundamental mode)	0.1178 ± 0.0013	0.1182 ± 0.0013
Ratio ($\frac{\text{cell average value}}{\text{depleted uranium value}}$)	0.996+)	0.992 ± 0.005
Cell average value of spectral indices in fundamental mode	0.117 ± 0.0015	0.116 ± 0.0015

+) Calculated factors

Table V-5 Reaction rate ratio, HARMONIE UK 5

Reaction rate ratios	σ_{f8}/σ_{f5}	σ_{c8}/σ_{f5}
Spectral indices in the reference position	0.0247 ± 0.00020	0.139 ± 0.0014
Corrected value $\overline{R_5}$	2.058 ± 0.009	2.058 ± 0.009
Corrected value $\overline{R_{f8}}$	2.033 ± 0.009	
Corrected value $\overline{R_{c8}}$		1.770 ± 0.009
Cell average value of spectral indices in fundamental mode	0.0244 ± 0.0025	0.119 ± 0.0015

Table VII-1 Calculated cell parameters

		UK 1	SNEAK-8	SNEAK-8Z	UK 5
k^*	MOXTOT	0.9756	0.9778	0.9950	1.0531
	KFKINR	0.9949	0.9964	1.0136	1.0725
	CAD II	1.0015	1.0029	1.0203	1.0784
k^+	CAD II	1.0011	1.0022	1.0156	1.0603
k_∞	MOXTOT	0.9805	0.9817	0.9956	1.0428
	KFKINR	0.9960	0.9967	1.0104	1.0576
	CAD II	1.0011	1.0022	1.0156	1.0602
$B^2\left(m^{-2}\right)$	MOXTOT	- 3.03	- 2.61	- 0.39	6.83
	KFKINR	- 0.59	- 0.18	1.72	8.49
	CAD II	0.18	0.35	2.51	9.68

Table VII-2 Calculated spectral indices (fundamental mode)

		UK 1	SNEAK-8	SNEAK-8Z	UK 5
σ_{f8}/σ_{f5}	MOXTOT	0.01882	0.01909	0.01942	0.02090
	KFKINR	0.02215	0.02243	0.02276	0.02443
	CAD II	0.02255	0.02277	0.02313	0.02486
σ_{f9}/σ_{f5}	MOXTOT	1.035	1.031	1.033	1.048
	KFKINR	1.124	1.118	1.120	1.136
	CAD II	1.080	1.084	1.084	1.095
σ_{c8}/σ_{f5}	MOXTOT	0.1165	0.1169	0.1162	0.1150
	KFKINR	0.1203	0.1209	0.1204	0.1188
	CAD II	0.1131	0.1137	0.1130	0.1113
σ_{c5}/σ_{f5}	MOXTOT	0.2302	0.2325	0.2303	0.2251
	KFKINR	0.2060	0.2081	0.2066	0.2015
	CAD II	0.2649	0.2672	0.2645	0.2581
σ_{cSt}/σ_{f5}	MOXTOT	0.0076	0.0069	0.0069	0.0076
	KFKINR	0.0075	0.0068	0.0068	0.0076
	CAD II	0.0057	0.0052	0.0052	0.0059

Table VII-3 Calculated spectral indices (static mode, $B^2 = 0$)

		UK 1	SNEAK-8	SNEAK-8Z	UK 5
σ_{f8}/σ_{f5}	MOXTOT	0.01917	0.01943	0.01947	0.01992
	KFKINR	0.02220	0.02246	0.02249	0.02299
	CAD II	0.02248	0.02271	0.02276	0.02336
σ_{f9}/σ_{f5}	MOXTOT	1.036	1.031	1.033	1.044
	KFKINR	1.124	1.118	1.120	1.131
	CAD II	1.079	1.084	1.082	1.089
σ_{c8}/σ_{f5}	MOXTOT	0.1163	0.1167	0.1163	0.1155
	KFKINR	0.1203	0.1209	0.1205	0.1194
	CAD II	0.1132	0.1137	0.1133	0.1124
σ_{c5}/σ_{f5}	MOXTOT	0.2295	0.2319	0.2302	0.2266
	KFKINR	0.2060	0.2080	0.2069	0.2035
	CAD II	0.2650	0.2673	0.2654	0.2618
σ_{cSt}/σ_{f5}	MOXTOT	0.0076	0.0069	0.0069	0.0076
	KFKINR	0.0075	0.0068	0.0068	0.0076
	CAD II	0.0057	0.0052	0.0052	0.0058

Table VII-4 Calculated reactivity worths

		UK 1	SNEAK-8	SNEAK-8Z	UK 5
$\frac{\delta k_8}{\delta k_5}$	KFKINR	-0.0590	-0.0590	-0.0589	-0.0588
	CAD II	-0.0582	-0.0585	-0.0583	-0.0579
$\frac{\delta k_{SS}}{\delta k_5}$	KFKINR		-0.0729	-0.0732	
	CAD II	-0.0602	-0.0596	-0.0601	-0.0621
$\frac{\delta k_{Ni}}{\delta k_5}$	KFKINR		-0.0813	-0.0811	
	CAD II	-0.0841	-0.0855	-0.0861	-0.0862

Table VII-5 Comparison of measured and calculated multiplication factors

		UK 1	SNEAK-8	SNEAK-8Z	UK 5 ERMINE	UK 5 HARMONIE
Experiment		0.9970 ± 0.0026	1.0065 ± 0.0018	1.0185 ± 0.0020	1.0645 ± 0.0037	1.0630 ± 0.0035
k_∞ $\frac{C-E}{C}$ %	MOXTOT	- 1.6	- 2.4	- 2.2	- 2.2	- 2.0
	KFKINR	- 0.1	- 0.9	- 0.8	- 0.7	- 0.5
	CAD II	+ 0.4	- 0.4	- 0.3	- 0.5	- 0.3
	CAD III	+ 0.4	- 0.4	- 0.3	- 0.3	- 0.1
Experiment		0.9970 ± 0.0026	1.0085 ± 0.0018	1.0220 ± 0.0020	1.0840 ± 0.0045	1.0810 ± 0.0050
k^* $\frac{C-E}{C}$ %	KFKINR	- 0.2	- 1.2	- 0.8	- 1.2	- 0.9
	CAD II	+ 0.4	- 0.5	- 0.2	- 0.6	- 0.3
	CAD III	+ 0.4	- 0.5	- 0.1	- 0.4	- 0.1

Table VII-6 Comparison of measured and calculated spectral indices

		UK 1 ERMINE	SNEAK-8	SNEAK-8Z	UK 5 ERMINE	UK 5 HARMONIE
σ_{f8}/σ_{f5} F.M.	Experiment	0.0220 ± 1%	0.0224 ± 2%	0.0227 ± 2%	0.0243 ± 1%	0.0244 ± 1%
	$\frac{C-E}{C}$ % KFKINR	+ 0.7	+ 0.1	+ 0.3	+ 0.5	+ 0.1
	$\frac{C-E}{C}$ % CAD II	+ 2.6	+ 1.6	+ 1.9	+ 2.2	+ 1.9
	$\frac{C-E}{C}$ % CAD III	+ 1.9	+ 1.2	+ 1.5	+ 1.8	+ 1.5
σ_{f8}/σ_{f5} St.M.	Experiment	0.0221 ± 1%	0.0222 ± 2%	0.0222 ± 2%	0.0228 ± 1%	0.0229 ± 1%
	$\frac{C-E}{C}$ % MOXTOT	- 15.3	- 14.2	- 14.0	- 14.5	- 15.0
	$\frac{C-E}{C}$ % KFKINR	+ 0.5	+ 1.2	+ 1.3	+ 0.8	+ 0.4
	$\frac{C-E}{C}$ % CAD II	+ 2.4	+ 2.2	+ 2.5	+ 2.5	+ 2.1
	$\frac{C-E}{C}$ % CAD III	+ 1.7	+ 1.9	+ 2.0	+ 2.1	+ 1.7
σ_{f9}/σ_{f5}		F.M.	St.M.		F.M.	
	Experiment	1.095 ± 1%	1.094 ± 2%		1.105 ± 1%	
	$\frac{C-E}{C}$ % MOXTOT	- 5.8	- 6.2		- 5.5	
	$\frac{C-E}{C}$ % KFKINR	+ 2.6	+ 2.1		+ 2.7	
	$\frac{C-E}{C}$ % CAD II	- 1.4	- 0.9		- 0.9	
	$\frac{C-E}{C}$ % CAD III	- 0.3	+ 0.1		0.0	
σ_{c8}/σ_{f5}		F.M.	St.M.		F.M.	F.M.
	Experiment	0.117 ± 1.4%	0.115 ± 2%		0.116 ± 1.4%	0.119 ± 1.4%
	$\frac{C-E}{C}$ % MOXTOT	- 0.4	+ 1.5		- 0.9	- 3.5
	$\frac{C-E}{C}$ % KFKINR	+ 2.7	+ 4.9		+ 2.4	- 0.2
	$\frac{C-E}{C}$ % CAD II	- 3.4	- 1.1		- 4.2	- 6.9
	$\frac{C-E}{C}$ % CAD III	+ 0.8	+ 3.0		+ 0.2	- 2.4

F.M. = Fundamental Mode St.M. = Static Mode

Table VII-7 Spectrum measurements with proton recoil counters: Experiment and comparison with CEA calculations

Energy limits (MeV)	UK 5		SNEAK-8	
	Experiment	$\frac{C-E}{C}$ in %	Experiment	$\frac{C-E}{C}$ in %
1.35 - 0.82	0.068	+ 21 ± 7	0.070	+ 19 ± 7
0.82 - 0.498	0.137	+ 19 ± 5	0.145	+ 18 ± 5
0.498 - 0.302	0.197	- 5 ± 5	0.216	- 9 ± 5
0.302 - 0.183	0.187	- 19 ± 5	0.204	- 20 ± 5
0.183 - 0.111	0.153	- 14 ± 5	0.170	- 15 ± 5
0.111 - 0.0674	0.120	- 21 ± 5	0.119	- 7 ± 5
0.0674 - 0.0409	0.081	+ 14 ± 5	0.076	+ 30 ± 7
0.0409 - 0.0248	0.037	+ 29 ± 7		
0.0248 - 0.015	0.020	+ 5 ± 11		

Table VII-8 Neutron balance with basic data from KFKINR (fundamental mode)

		UK 1	SNEAK-8	UK 5 ERMINE	UK 5 HARMONIE
Production					
ν_5	(b)	2.479	2.479	2.482	2.482
$\nu_8 \frac{N_8}{N_5} \frac{\sigma_{f8}}{\sigma_{f5}}$	(a)	1.013 ± 0.010	1.017 ± 0.02	0.979 ± 0.01	0.983 ± 0.01
Numerator		3.492 ± 0.010	3.496 ± 0.02	3.461 ± 0.01	3.465 ± 0.01
Absorption					
$1 + \alpha_5$	(b)	1.206	1.208	1.202	1.202
$\frac{N_8}{N_5} \frac{\sigma_{f8}}{\sigma_{f5}}$	(a)	0.357 ± 0.004	0.358 ± 0.007	0.345 ± 0.004	0.346 ± 0.004
$\frac{N_8}{N_5} \frac{\sigma_{c8}}{\sigma_{f5}}$	(a)	1.903 ± 0.03	1.844 ± 0.04 (1.892 ± 0.04)+)	1.645 ± 0.025	1.688 ± 0.025
Σ_{cSt}/Σ_{f5}	(b)	0.018	0.019	0.016	0.016
$-\Sigma_{n,2n}/\Sigma_{f5}$	(b)	-0.014	-0.014	-0.014	-0.014
Denominator		3.470 ± 0.03	3.415 ± 0.04 (3.463 ± 0.04)+)	3.194 ± 0.025	3.238 ± 0.025
$k^* = \frac{N}{D}$		1.006 ± 0.009	1.024 ± 0.012 (1.010 ± 0.012)+)	1.083 ± 0.009	1.070 ± 0.009
k^* from cell worth measurement		0.997 ± 0.0026	1.008 ± 0.002	1.084 ± 0.005	1.081 ± 0.005
Deviation, %		+ 0.9	+ 1.6 (0.2)+)	- 0.1	- 1.0
Data calculated with KFKINR					
ν_5		2.479	2.479	2.482	2.482
ν_8		2.840	2.838	2.840	2.840
α_5		0.206	0.208	0.202	0.202

(a) Measured (b) Calculated from basic data +) Measurements by Cadarache group

Table VII-9 Neutron balance with basic data from Cadarache version II (fundamental mode)

		UK 1	SNEAK-8	UK 5 ERMINE	UK 5 HARMONIE
Production					
ν_5	(b)	2.442	2.439	2.445	2.445
$\nu_8 \frac{N_8}{N_5} \frac{\sigma_{f8}}{\sigma_{f5}}$	(a)	1.003 ± 0.010	1.007 ± 0.02	0.967 ± 0.01	0.971 ± 0.01
Numerator		3.445 ± 0.010	3.446 ± 0.02	3.412 ± 0.01	3.416 ± 0.01
Absorption					
$1 + \alpha_5$	(b)	1.265	1.267	1.258	1.258
$\frac{N_8}{N_5} \frac{\sigma_{f8}}{\sigma_{f5}}$	(a)	0.357 ± 0.004	0.358 ± 0.007	0.345 ± 0.004	0.346 ± 0.004
$\frac{N_8}{N_5} \frac{\sigma_{c8}}{\sigma_{f5}}$	(a)	1.903 ± 0.03	1.844 ± 0.04 (1.892 ± 0.04)+)	1.645 ± 0.025	1.688 ± 0.025
Σ_{cSt}/Σ_{f5}	(b)	0.013	0.015	0.012	0.012
$-\Sigma_{n,2n}/\Sigma_{f5}$	(b)	-0.015	-0.015	-0.015	-0.015
Denominator		3.523 ± 0.03	3.469 ± 0.04 (3.517 ± 0.04)+)	3.245 ± 0.025	3.289 ± 0.025
$k^* = \frac{N}{D}$		0.978 ± 0.009	0.993 ± 0.012 (0.980 ± 0.012)+)	1.052 ± 0.009	1.039 ± 0.009
k^* from cell worth measurement		0.997 ± 0.0026	1.008 ± 0.002	1.084 ± 0.005	1.081 ± 0.005
Deviation, %		- 1.9	- 1.5 (- 2.8)+)	- 3.0	- 3.9
Data calculated with Cadarache version II					
ν_5		2.442	2.439	2.445	2.445
ν_8		2.810	2.809	2.810	2.810
α_5		0.265	0.267	0.258	0.258

(a) Measured (b) Calculated from basic data +) Measurements by Cadarache group

Table VIII-1 Minimum enrichments from ρ_8/ρ_5 method

Assembly	Minimum enrichment		Error contributions to ρ_8/ρ_5 (%)				
	ρ_8/ρ_5	E (a/o)	Material-measure-ments	Hetero-geneity	Impurities	Conversion to the pure uranium core	Total (rms)
ERMINE UK 1	-0.0589 ± 0.0004	5.63 ± 0.04	0.27	0.30	0.25	0.50	0.69
SNEAK-8	-0.0579 ± 0.0003	5.54 ± 0.03	0.10	0.25	0.25	0.50	0.62
SNEAK-8Z	-0.0581 ± 0.0004	5.56 ± 0.04	0.19	0.25	0.25	0.50	0.64
ERMINE UK 5	-0.0577 ± 0.0004	5.53 ± 0.04	0.34	0.30	0.25	0.50	0.72
Mean value	-0.0581 ± 0.0002	5.56 ± 0.02					

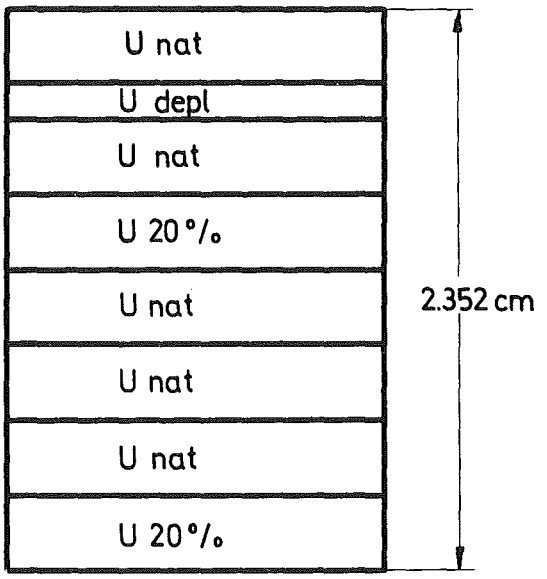
Table VIII-2 Reaction rate ratios with C/E method (KFKINR data set)

Assembly	C/E for σ_{f8}/σ_{f5}	C/E for σ_{f9}/σ_{f5}	C/E for σ_{c8}/σ_{f5}
ERMINE UK 1 a)	1.007	1.027	1.028
SNEAK-8 b)	1.012	1.021	1.05 GfK 1.025 Cad.
SNEAK-8Z b)	1.013	--	--
ERMINE UK 5 a)	1.005	1.028	1.024
HARMONIE UK 5 a)	1.001	--	0.998
Mean value	1.008 ± 0.008	1.025 ± 0.008	1.025 ± 0.015

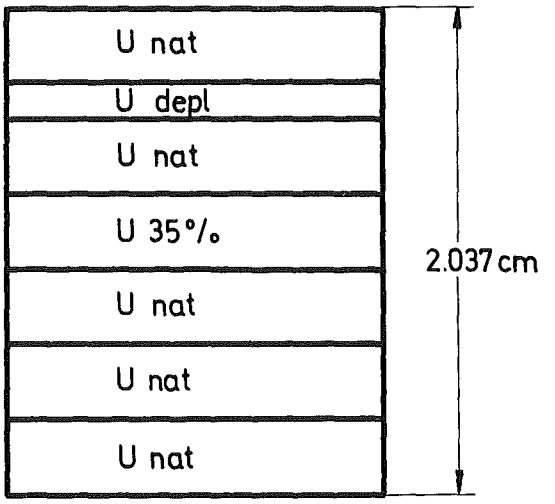
a) Fundamental Mode b) Static Mode

Table VIII-3 Calculated parameters for the minimum enrichment 5.56%

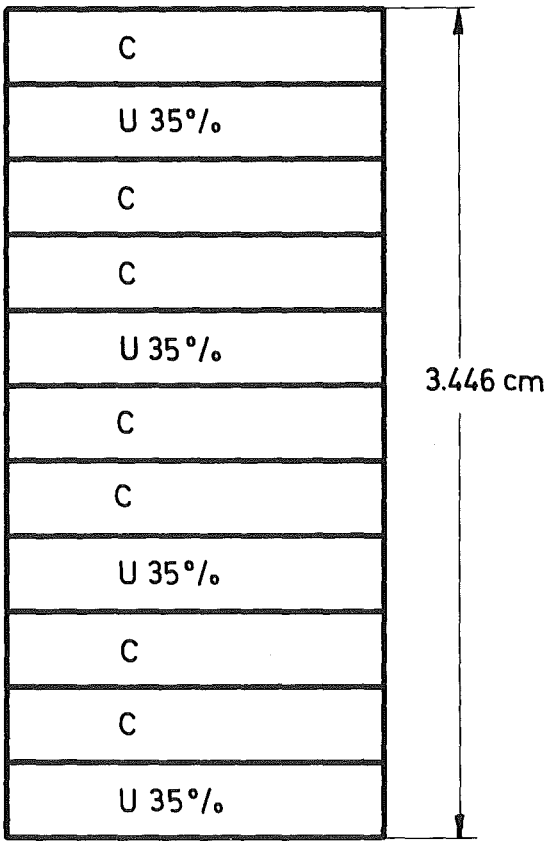
Data set	KFKINR (static mode)	Cadarache version III (fundamental mode)
k_∞ or k^+	0.9937	0.9988
B^2		-0.229×10^{-4}
σ_{f8}/σ_{f5}	0.02291	0.02307
σ_{f9}/σ_{f5}	1.124	1.1054
σ_{c8}/σ_{f5}	0.1195	0.1172



test zone SNEAK-8



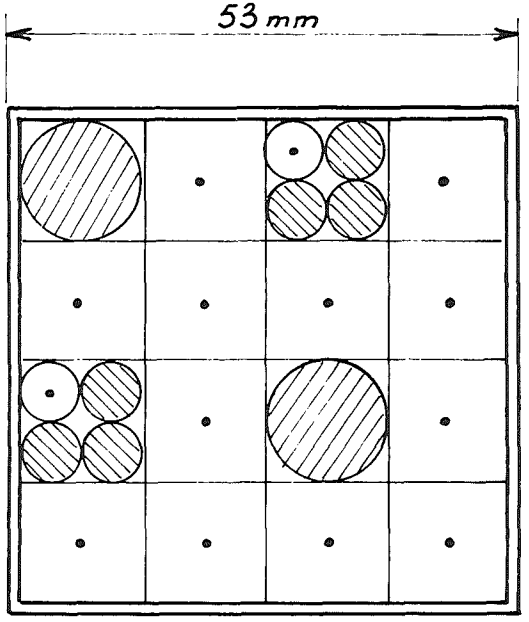
test zone SNEAK-8Z



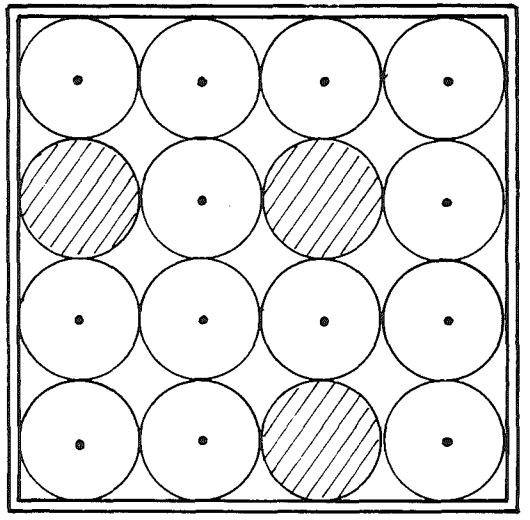
driver zone

Fig. II-1 Unit cells of the SNEAK cores

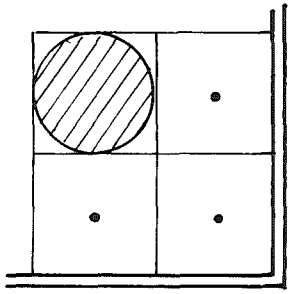
Fig. II-2 _ UNIT CELLS OF THE UK CORES



UK1



UK2



UK5

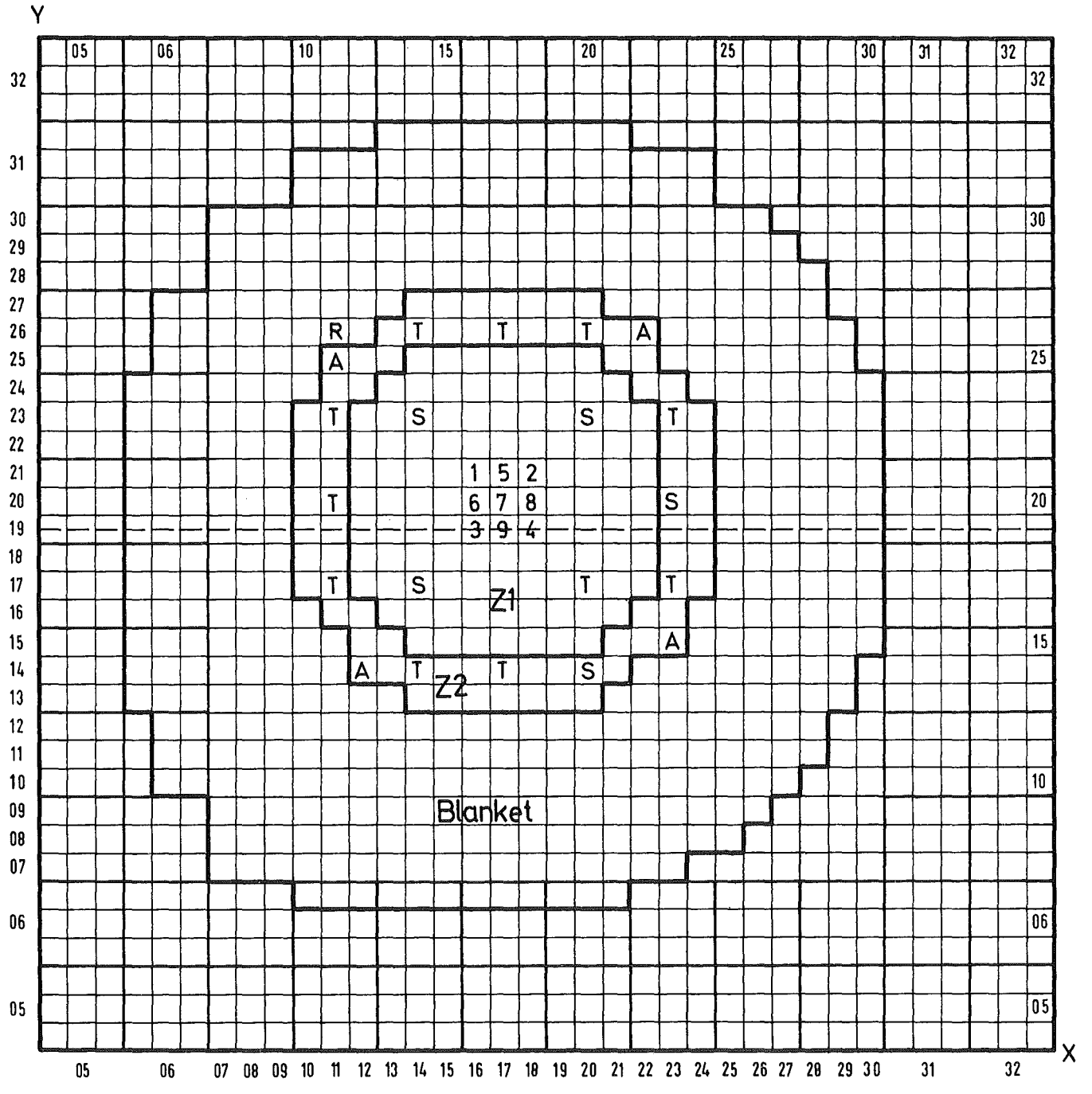
Uranium 30 %, ϕ 12,7 mm

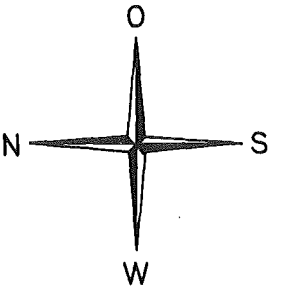
Uranium 30% ϕ 6,35 mm

Uranium depleted 0,42% □ 12,7 mm

Uranium depleted 0.42% ϕ 12,7 mm

Uranium depleted 0.42% ϕ 6,35 mm

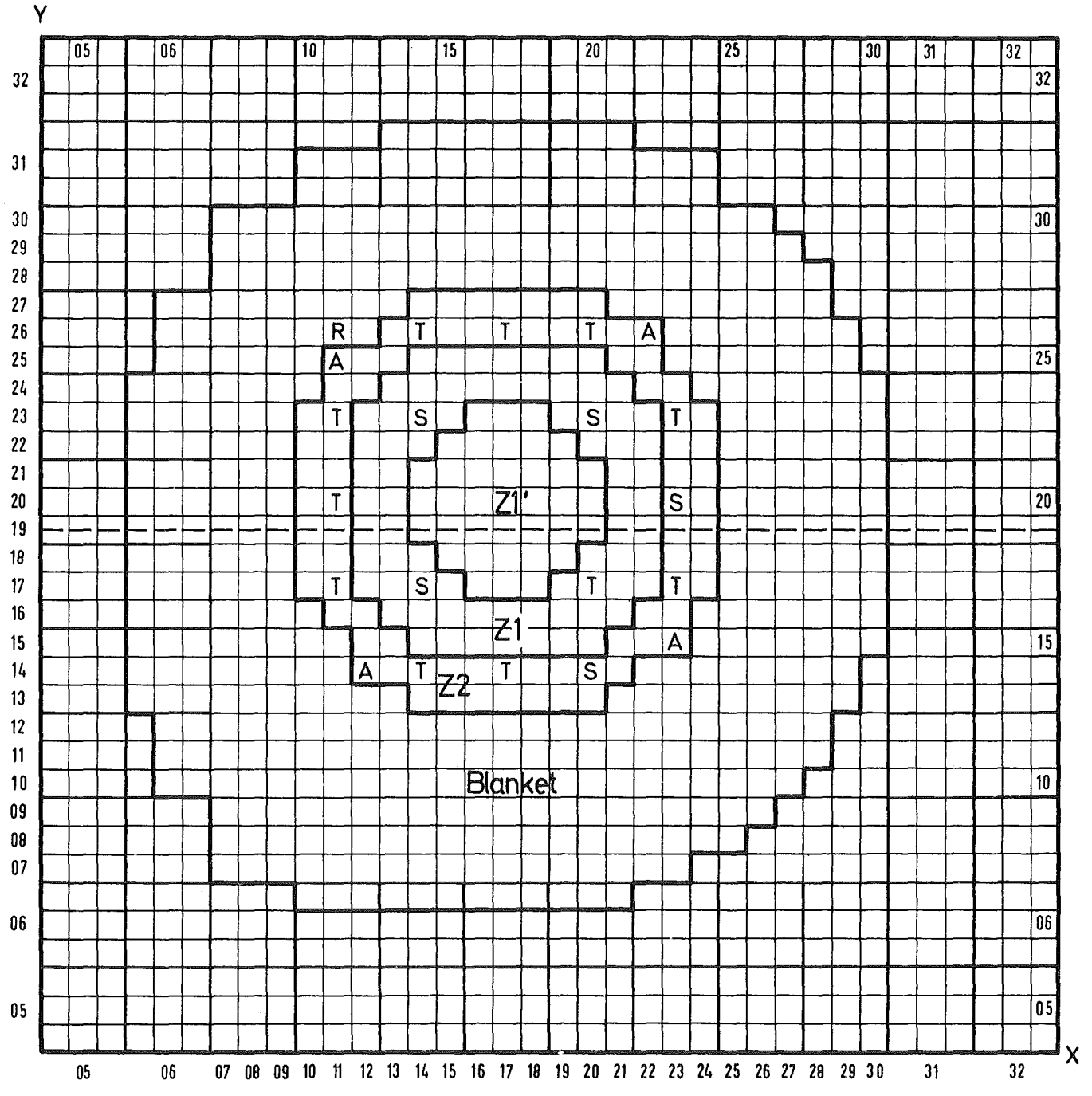




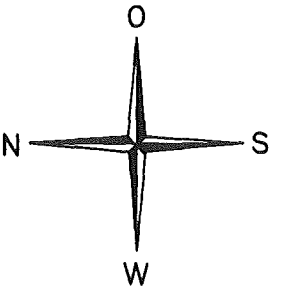
SNEAK - 8 Core map

Z1 test zone
Z2 driver zone
T shim rod
S safety rod
R fine control rod
A subassembly with reduced fuel loading
1-9 subassemblies used for cell worth measurements

Fig. II -3



SNEAK - 8Z Core map



Z1' test zone SNEAK - 8Z
Z1 test zone SNEAK - 8
Z2 driver zone
T shim rod
S safety rod
R fine control rod
A driver subassembly with reduced fuel loading

Fig. II - 4

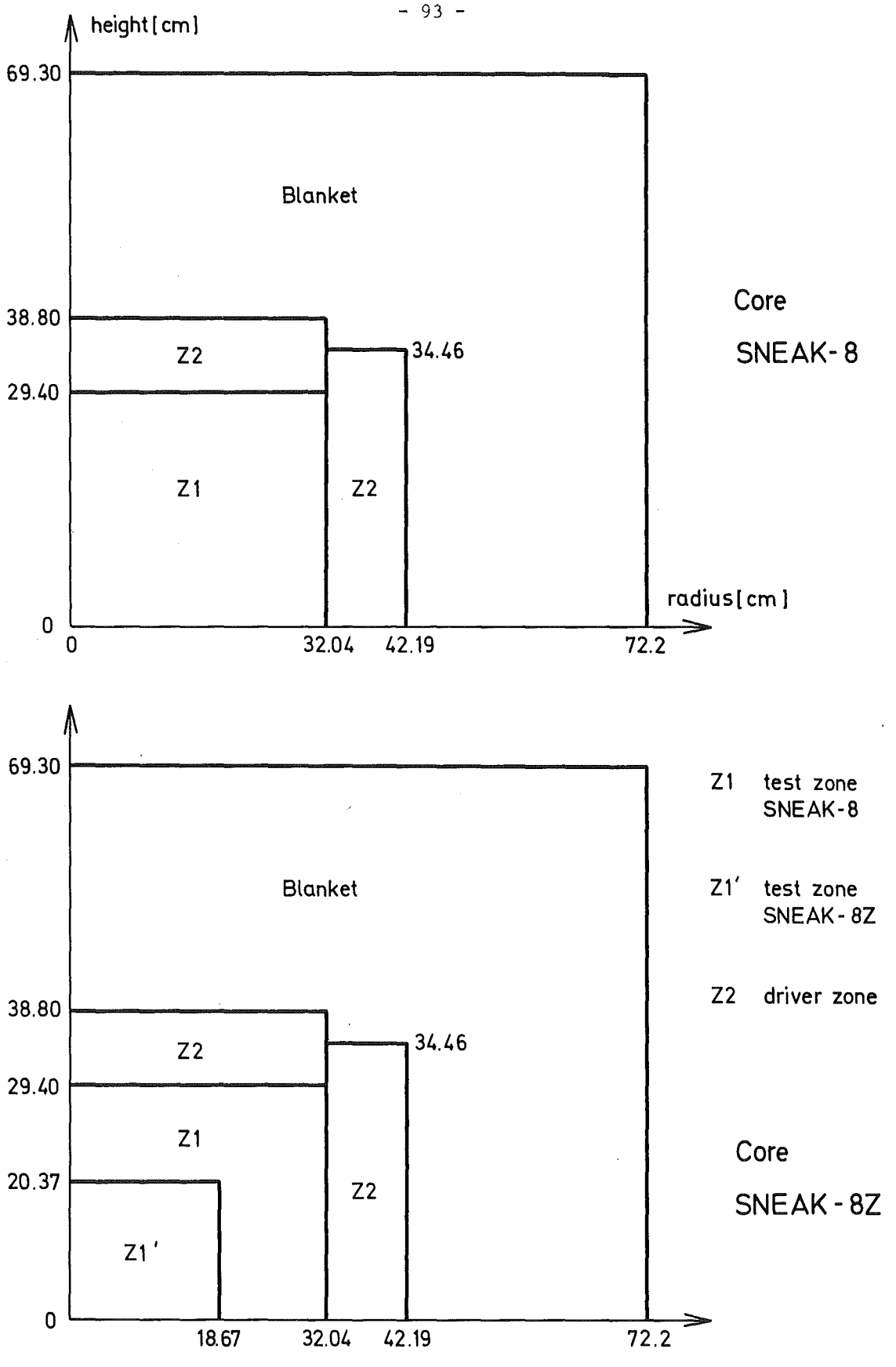
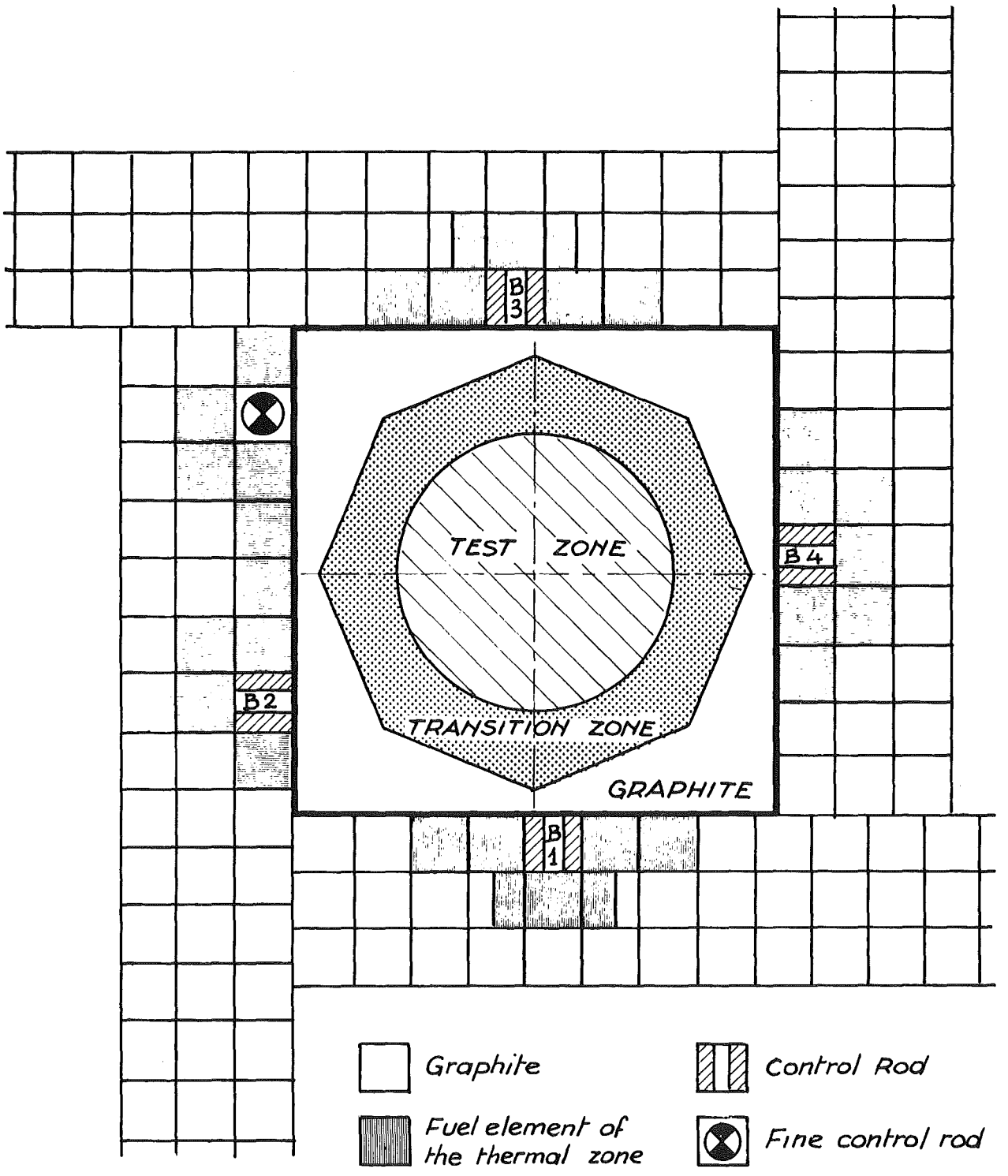
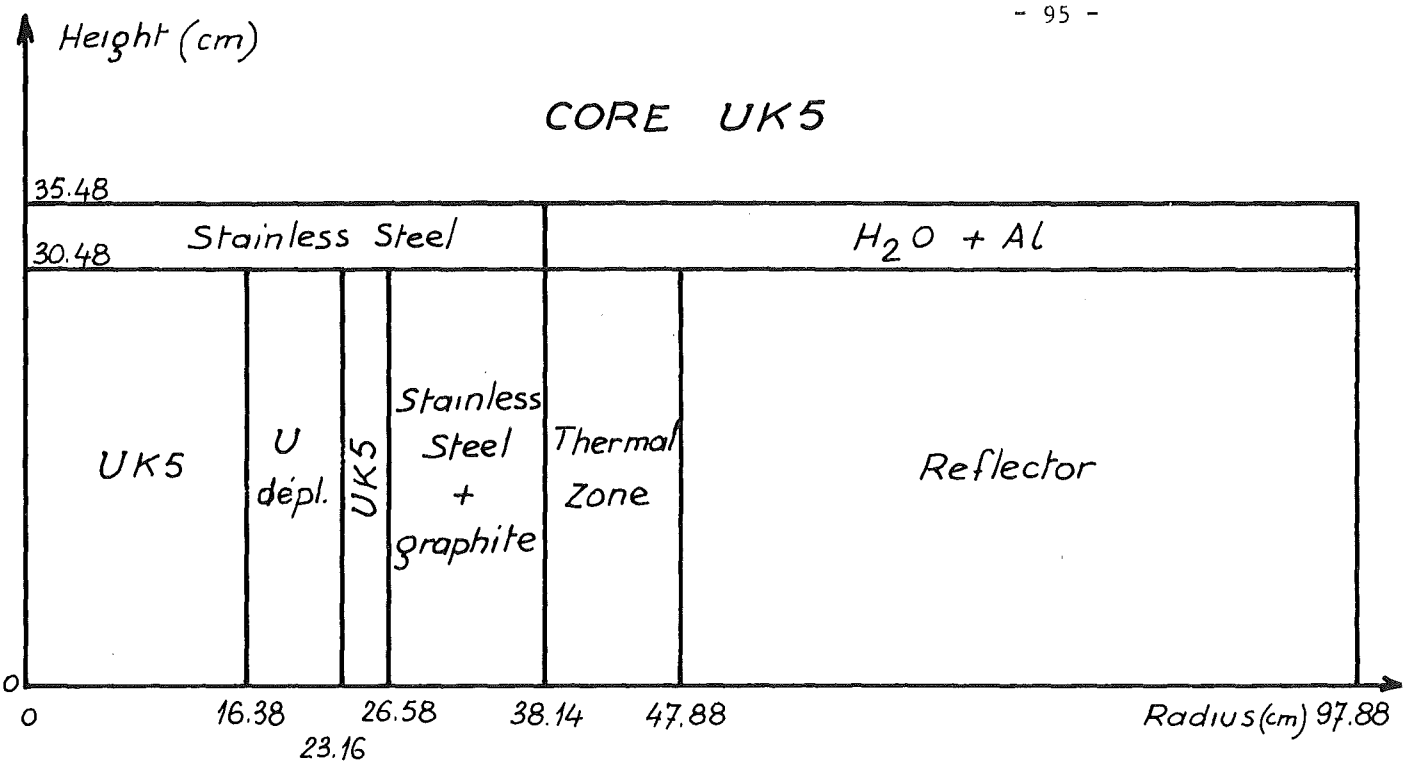


Fig. II-5 R-Z-Cross section of the SNEAK cores

Fig. II - 6

ERMINE 2 UK - CORE MAP





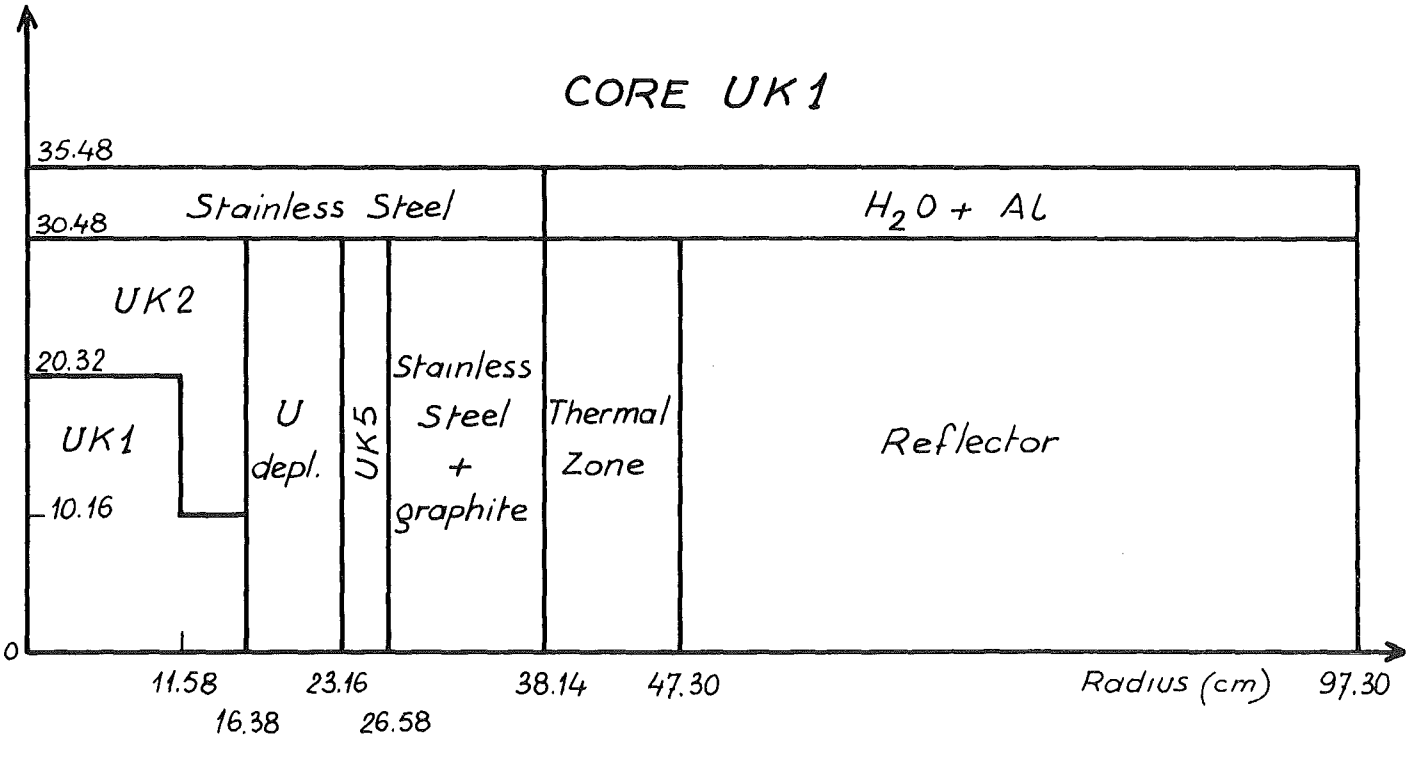


Fig. II-7 _ RZ CROSS SECTION OF ERMINE CORES : UK5 and UK1

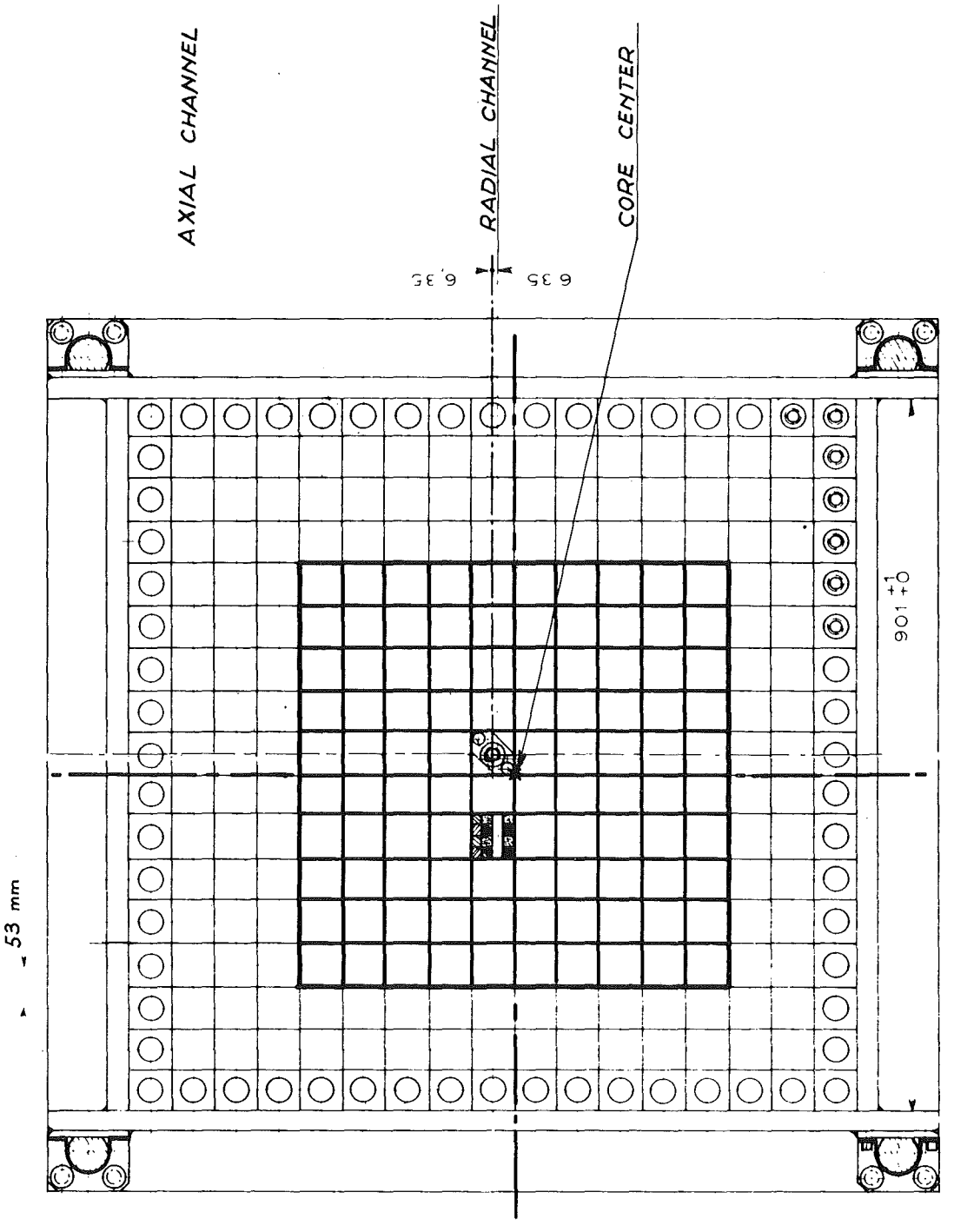
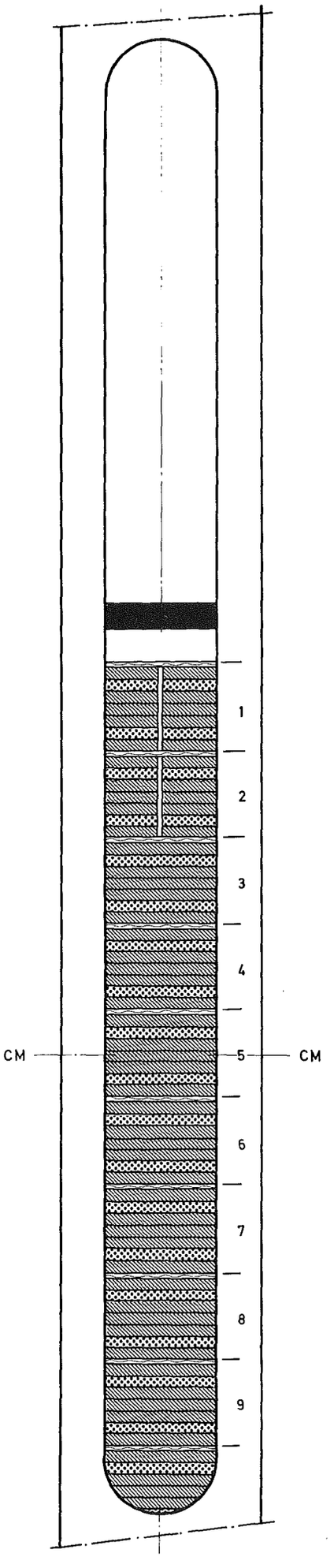


Fig. II.8 - UKS HARMONIE CORE MAP



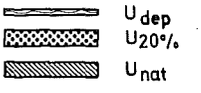
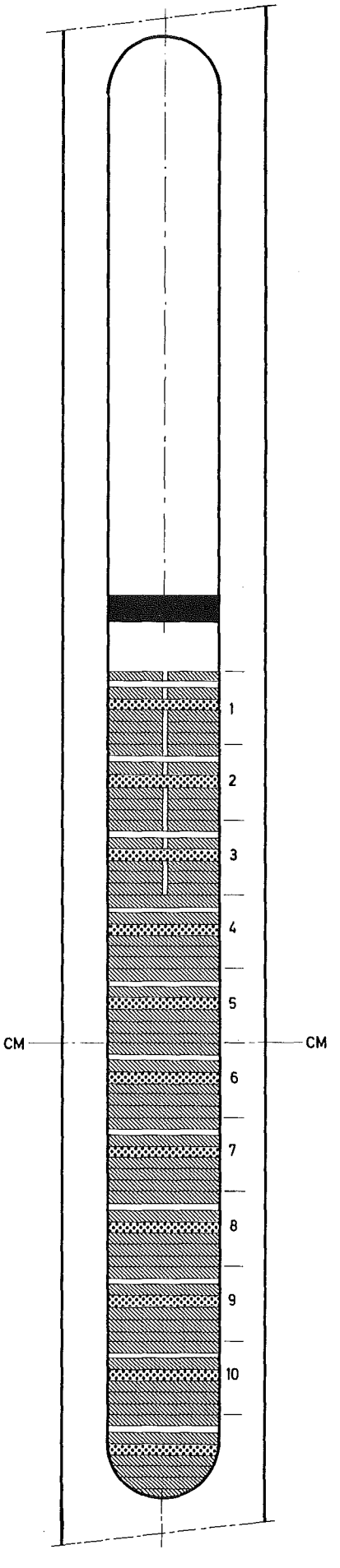


Fig. IV -1
Special Subassembly
SNEAK-8



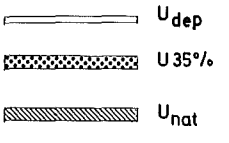
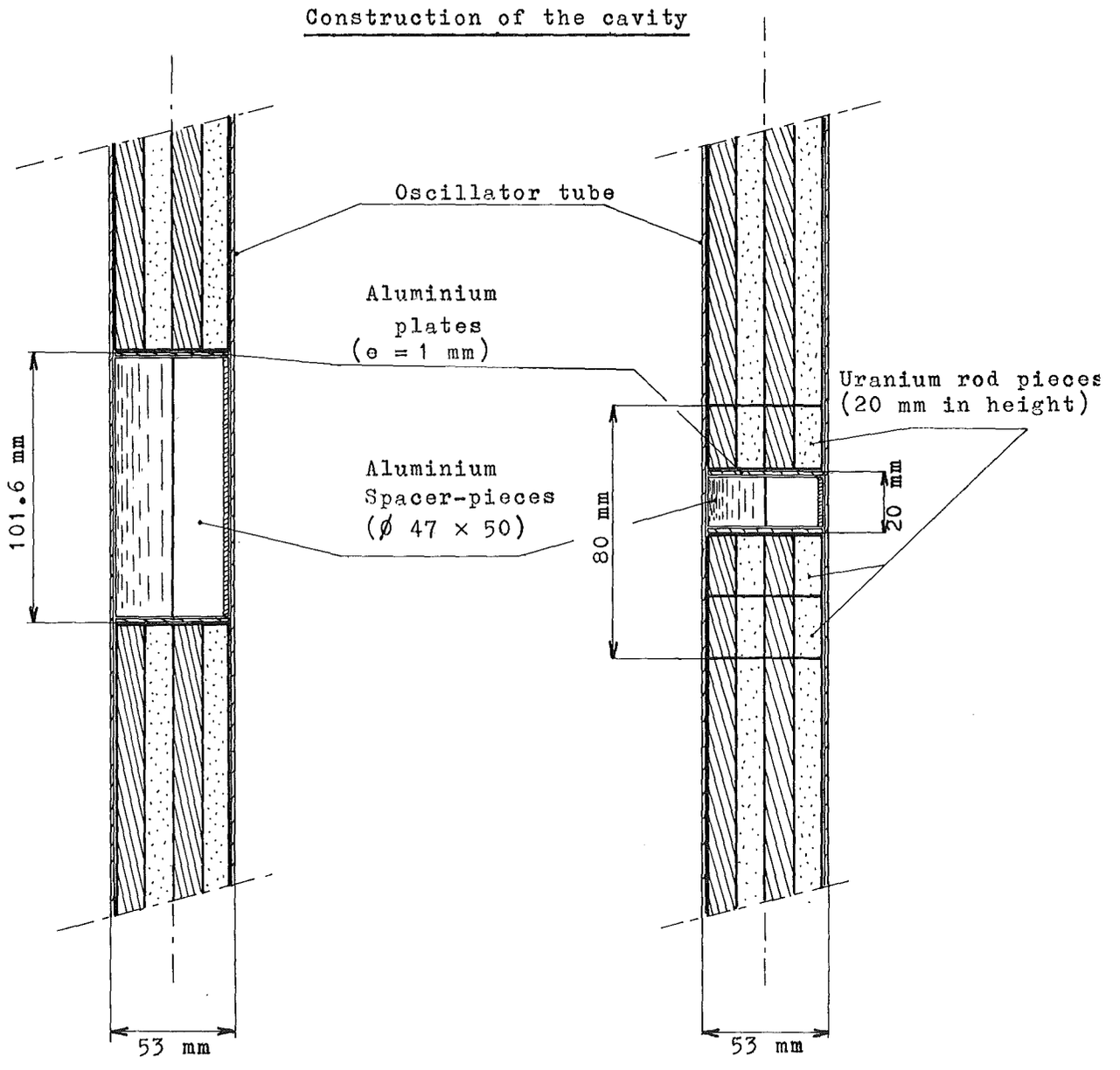


Fig. IV - 2
Special Subassembly
SNEAK - 8Z

Fig IV_3 : ERMINE UK1 and UK5



Height of cavity : 101.6 mm

Height of cavity : 20 mm

../...

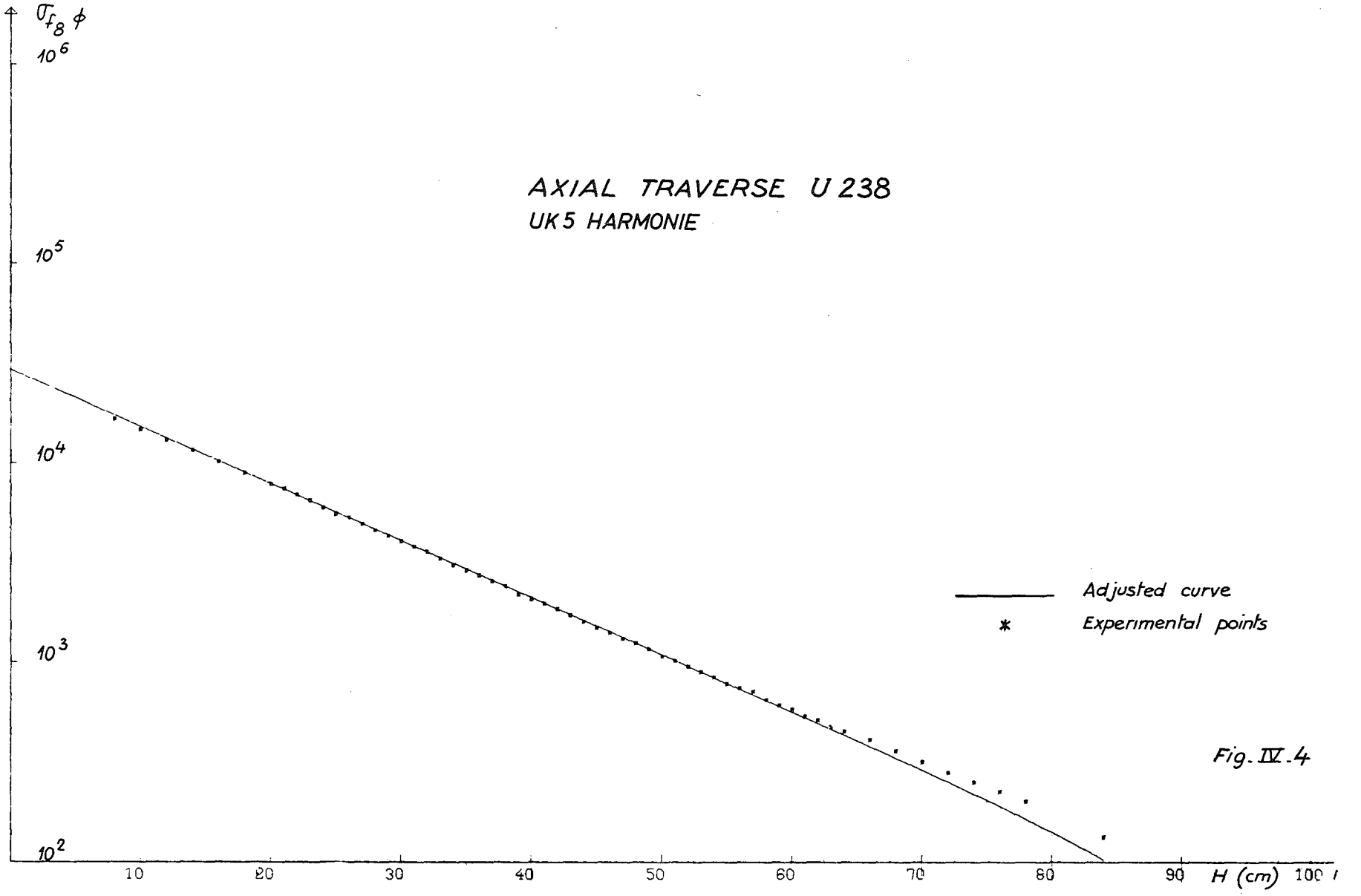

$\sigma_{f8}\,\phi$
10^6
10^5
10^4
10^3
10^2
10
20
30
40
50
60
70
80
90
H (cm)
100
AXIAL TRAVERSE U 238
UK 5 HARMONIE
Adjusted curve
Experimental points

Fig. IV.4

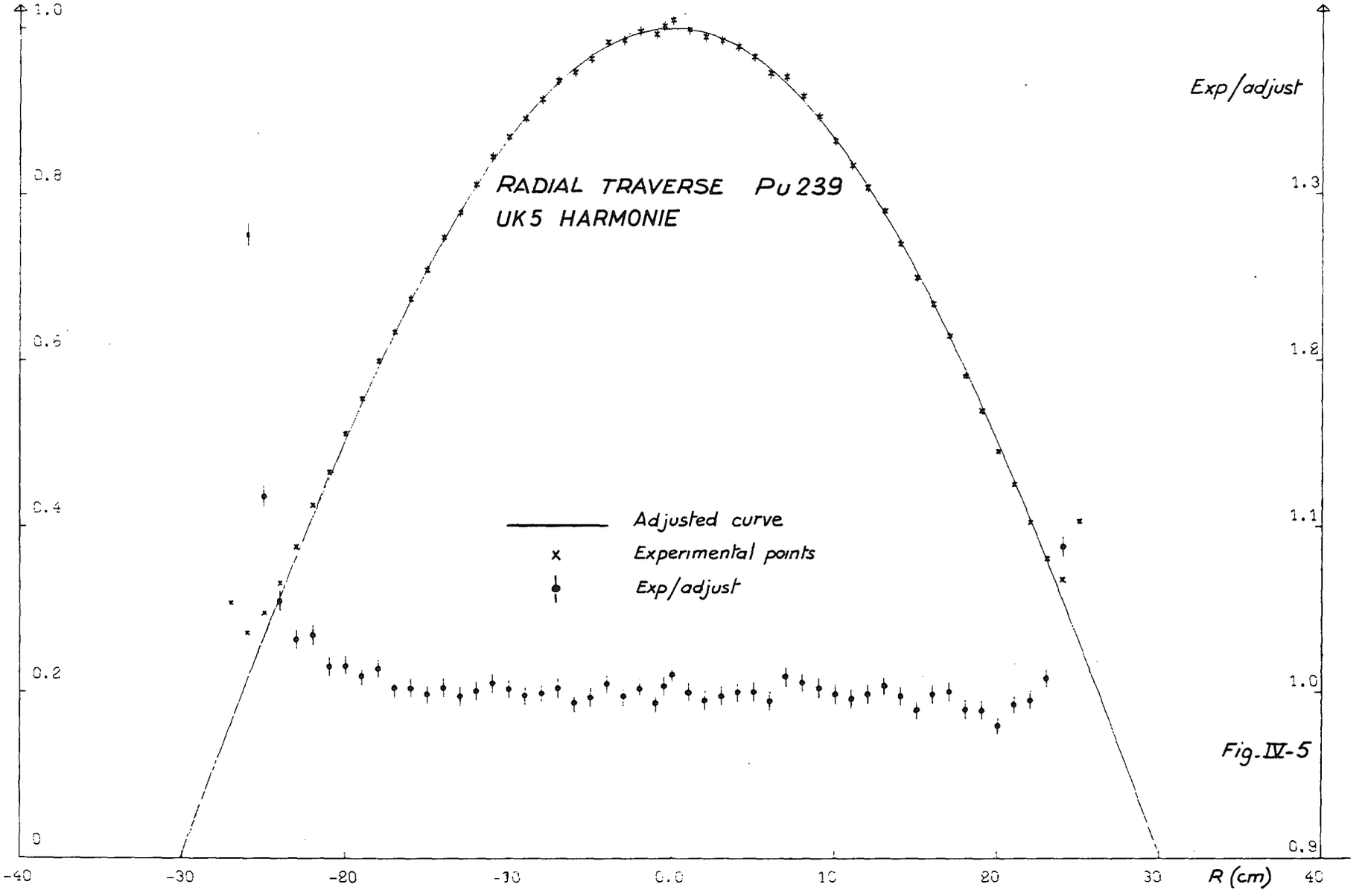

RADIAL TRAVERSE Pu 239
UK5 HARMONIE
Adjusted curve
Experimental points
Exp/adjust
Exp/adjust
1.0
0.8
0.6
0.4
0.2
0
1.3
1.2
1.1
1.0
0.9
-40
-30
-20
-10
0.0
10
20
30
40
R (cm)

Fig. IV-5

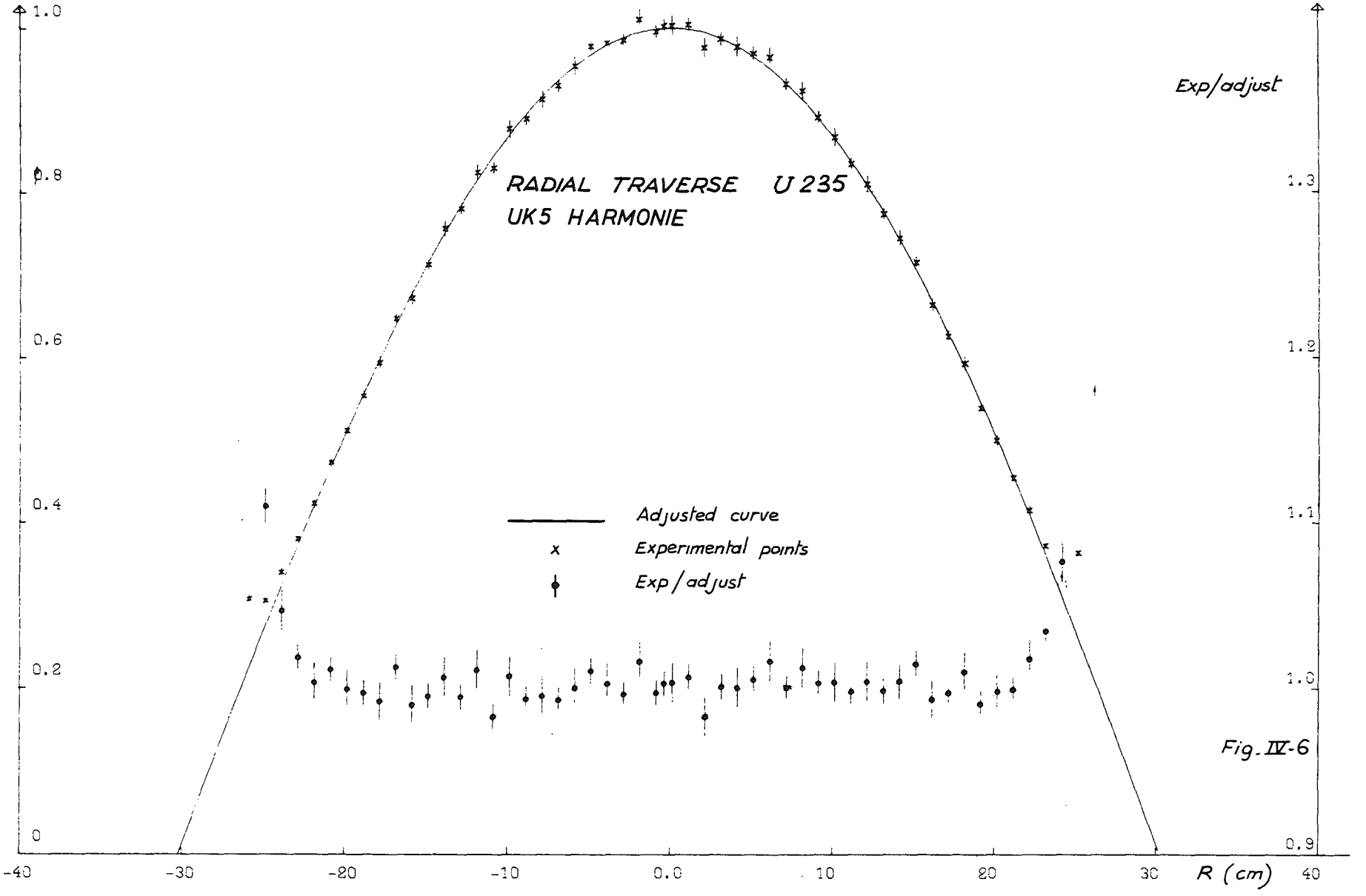

RADIAL TRAVERSE U 235
UK5 HARMONIE
Adjusted curve
Experimental points
Exp/adjust
Exp/adjust
1.0
0.8
0.6
0.4
0.2
0
1.3
1.2
1.1
1.0
0.9
-40
-30
-20
-10
0.0
10
20
30
40
R (cm)

Fig. IV-6

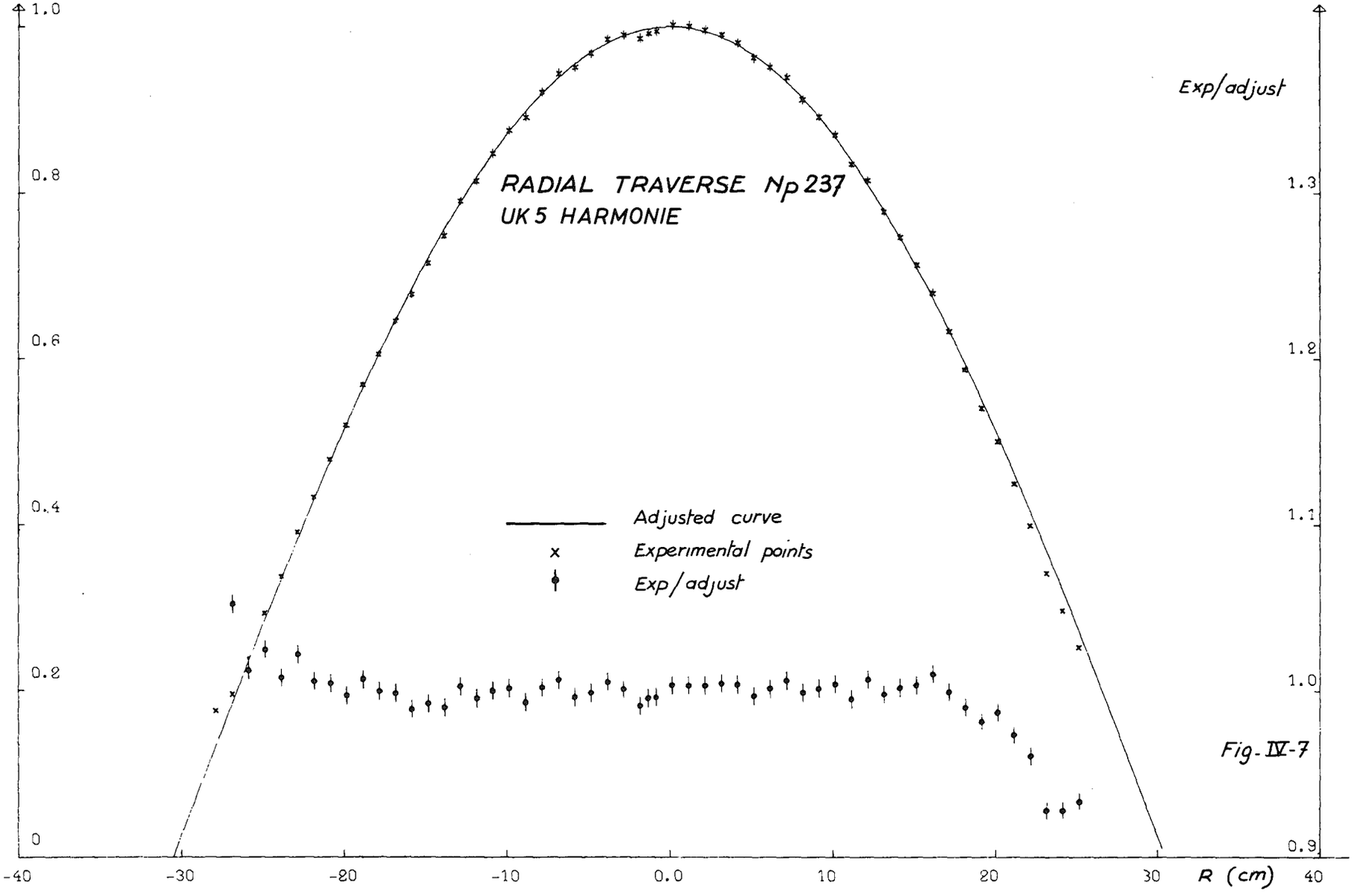

RADIAL TRAVERSE Np 237
UK 5 HARMONIE
Adjusted curve
Experimental points
Exp/adjust
Exp/adjust
1.0
0.8
0.6
0.4
0.2
0
1.3
1.2
1.1
1.0
0.9
-40
-30
-20
-10
0.0
10
20
30
40
R (cm)

Fig. IV-7

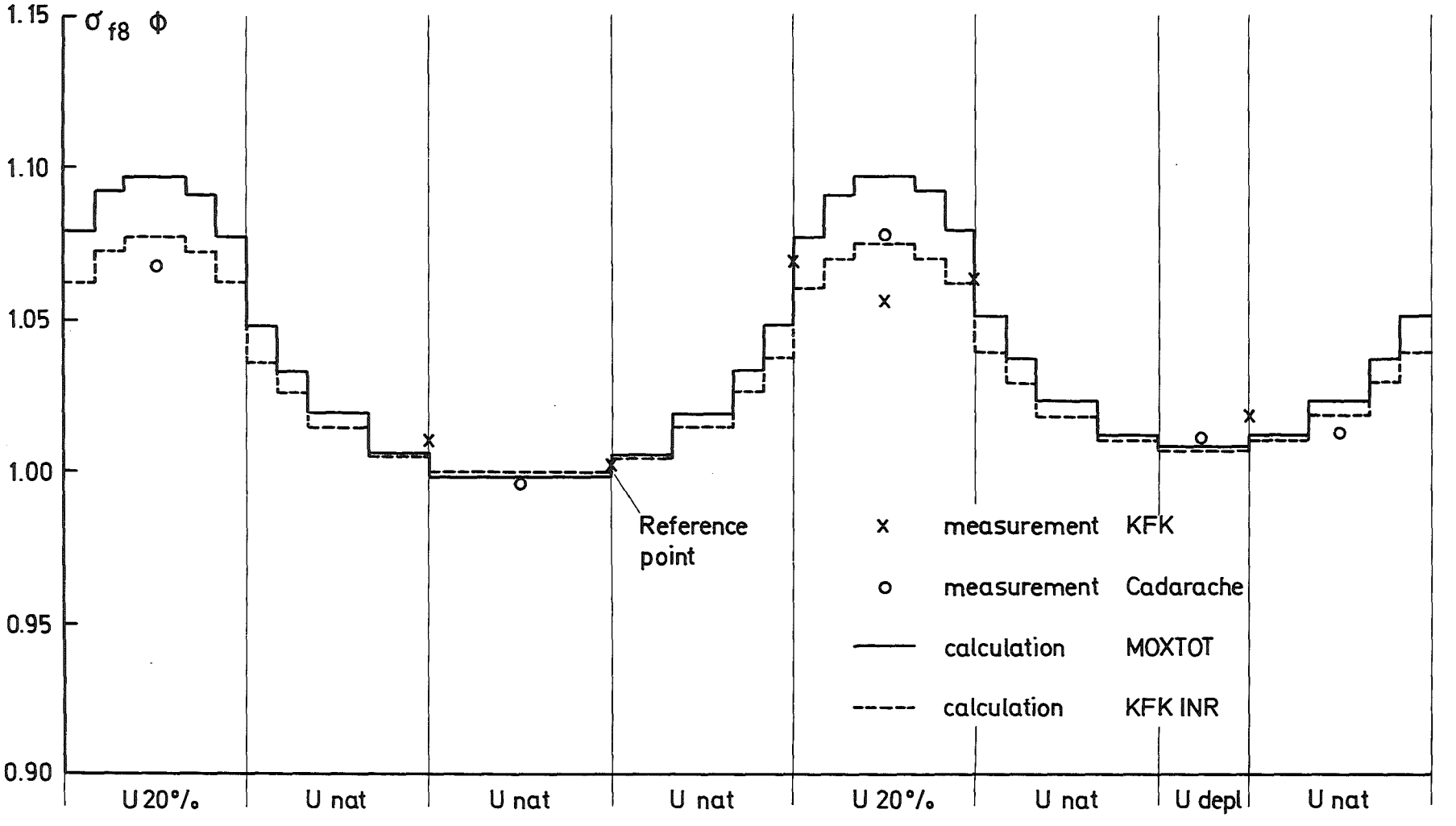


Fig. V-1 SNEAK-8 Fine structure of the fission rate σ_{f8} Φ in the unit cell

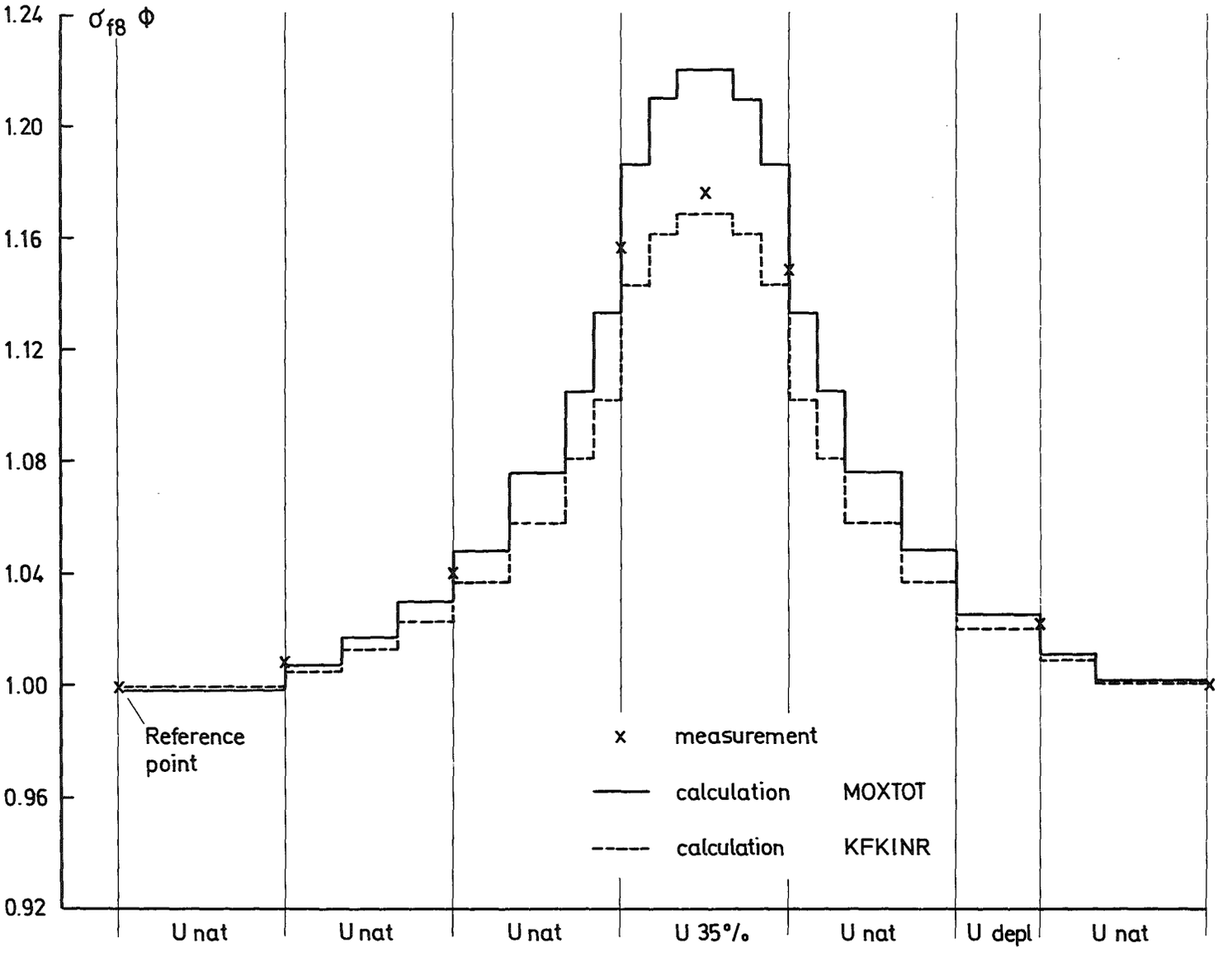
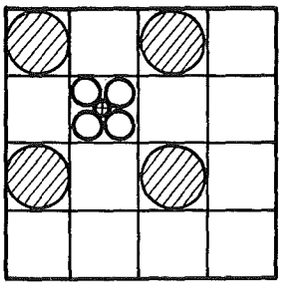


Fig. V-2 SNEAK-8Z Fine structure of the fission rate $\sigma_{f8}\,\Phi$ in the unit cell

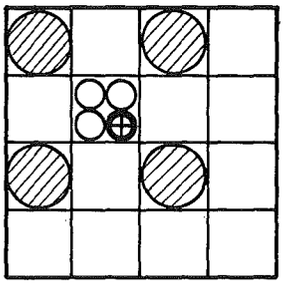
Fig V_3 : REACTION RATE RATIO MEASUREMENTS IN ERMINE

1/ Fission chambers measurements :



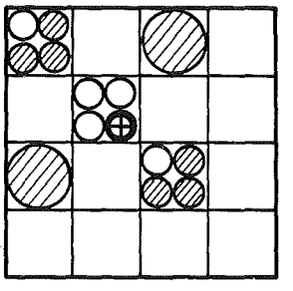
UK5

(chambers ∅ 1.5 mm)



UK5

(chambers ∅ 4 mm)

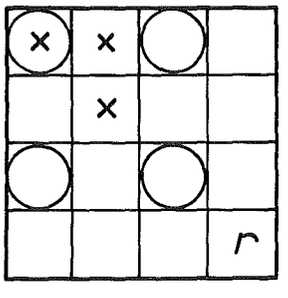


UK1

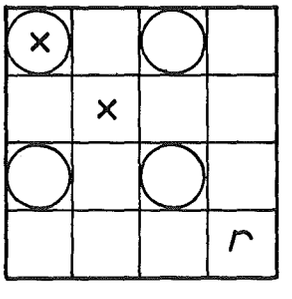
(chambers ∅ 4 mm)

⊕ Positions of the chambers

2/ Heterogeneity measurements :



σ_{f8} and f5

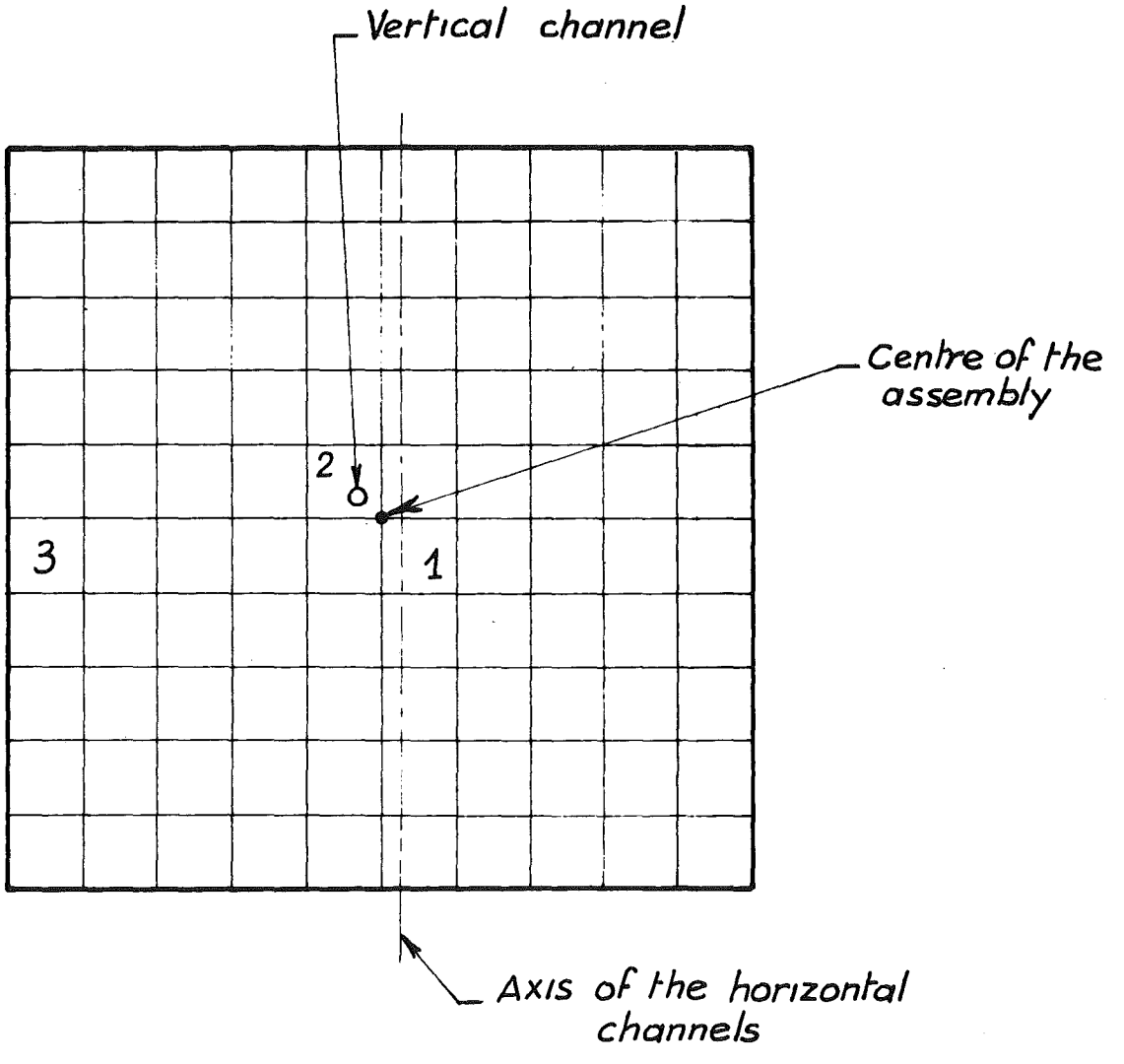


σ_{c8}

× Positions of the foils.

⌐ Parallel plate fission chambers with adjoining foils.

../...



1 } Tube used for the foil
2 } measurements

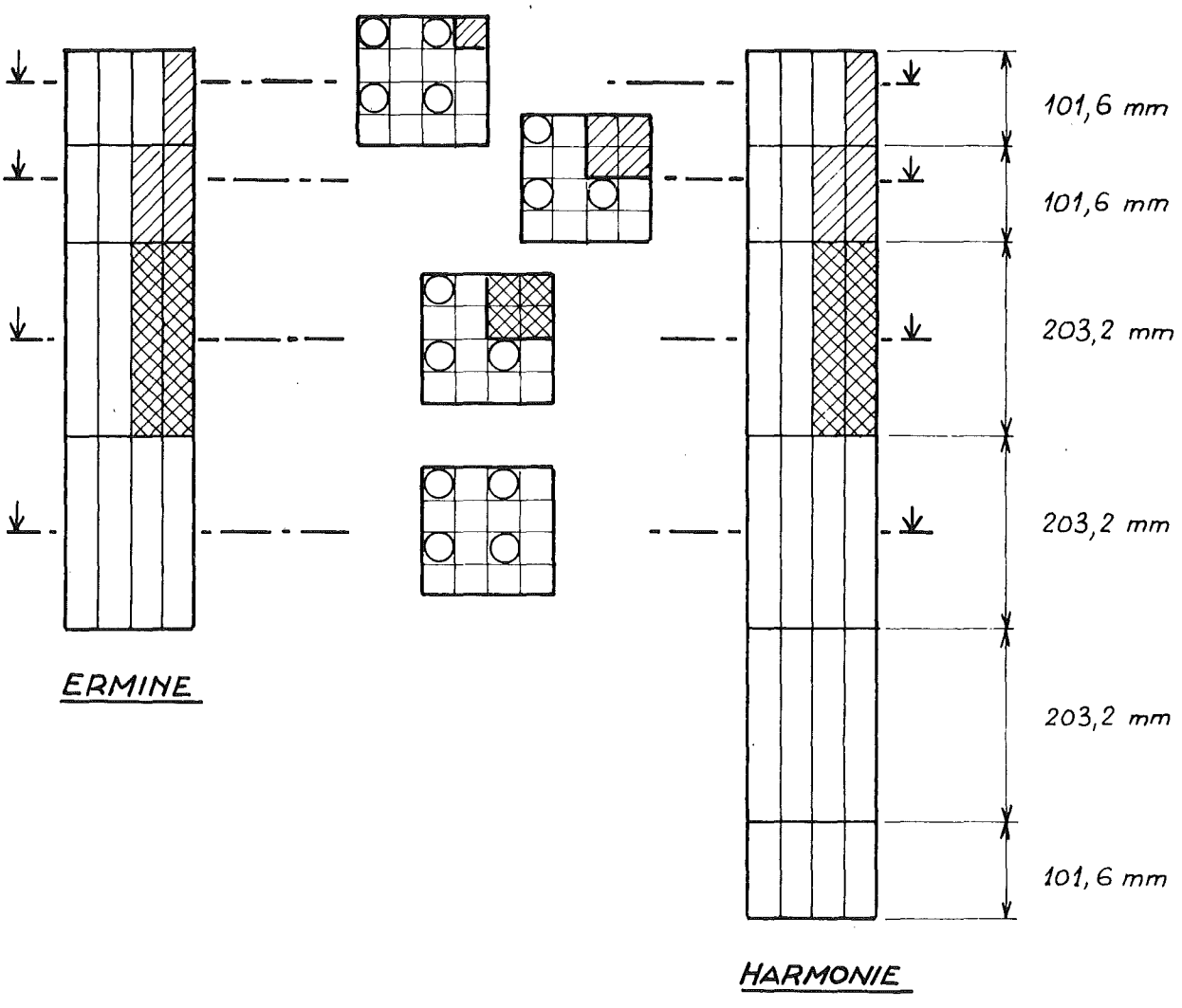
3 Reference position for the chamber measurements

HARMONIE - UK5

Horizontal cross section

Fig. V-4

UK5 - SPECTRUM MEASUREMENTS



⊠ Positions of the counters

▨ Removed rods

○ U 30 %

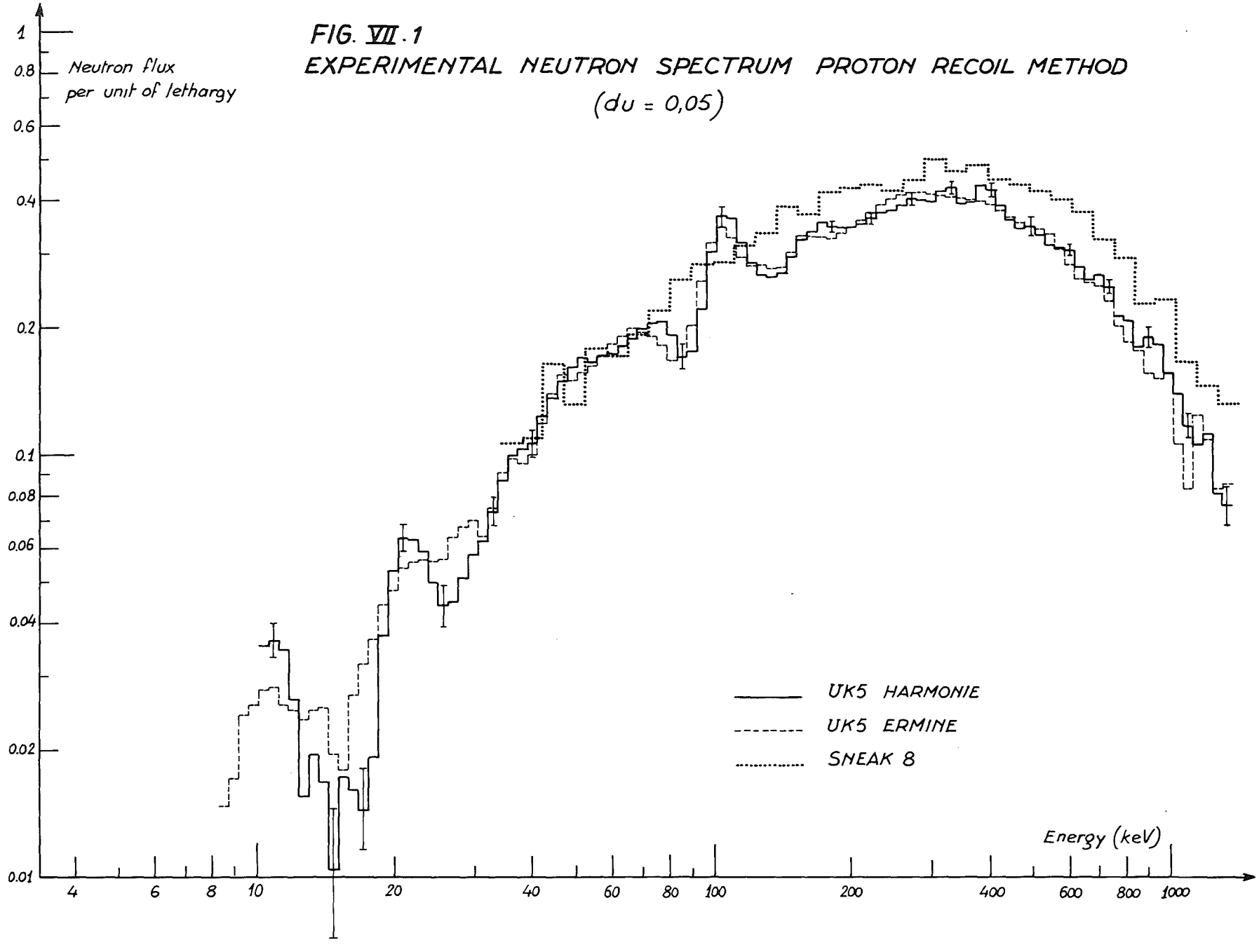
□ Depleted Uranium

Fig. VI - 1

FIG. VII.1

EXPERIMENTAL NEUTRON SPECTRUM PROTON RECOIL METHOD

(du = 0,05)



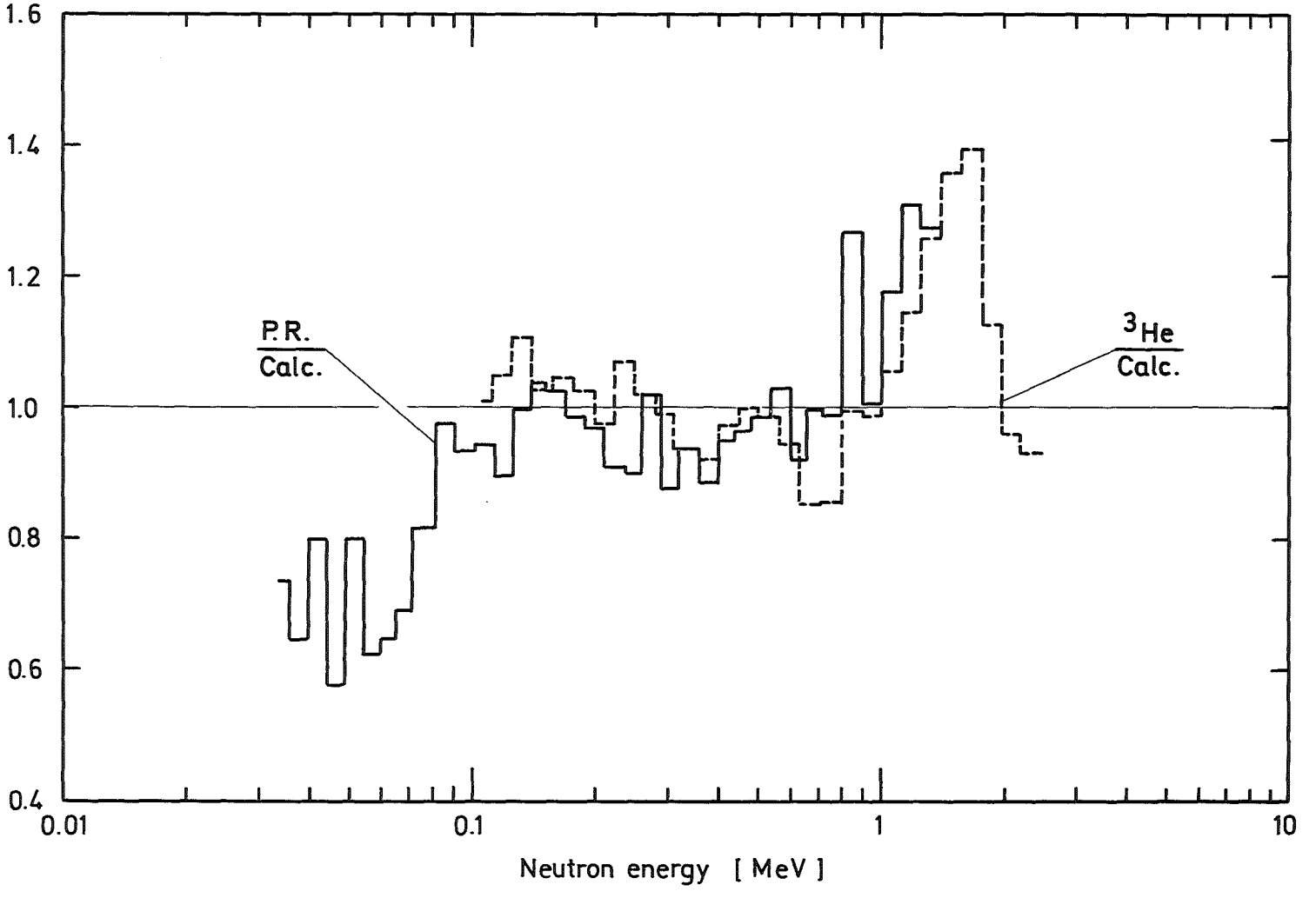


Fig. VII.2
SNEAK-8 Comparison of measured and calculated spectra
(Kedak data)

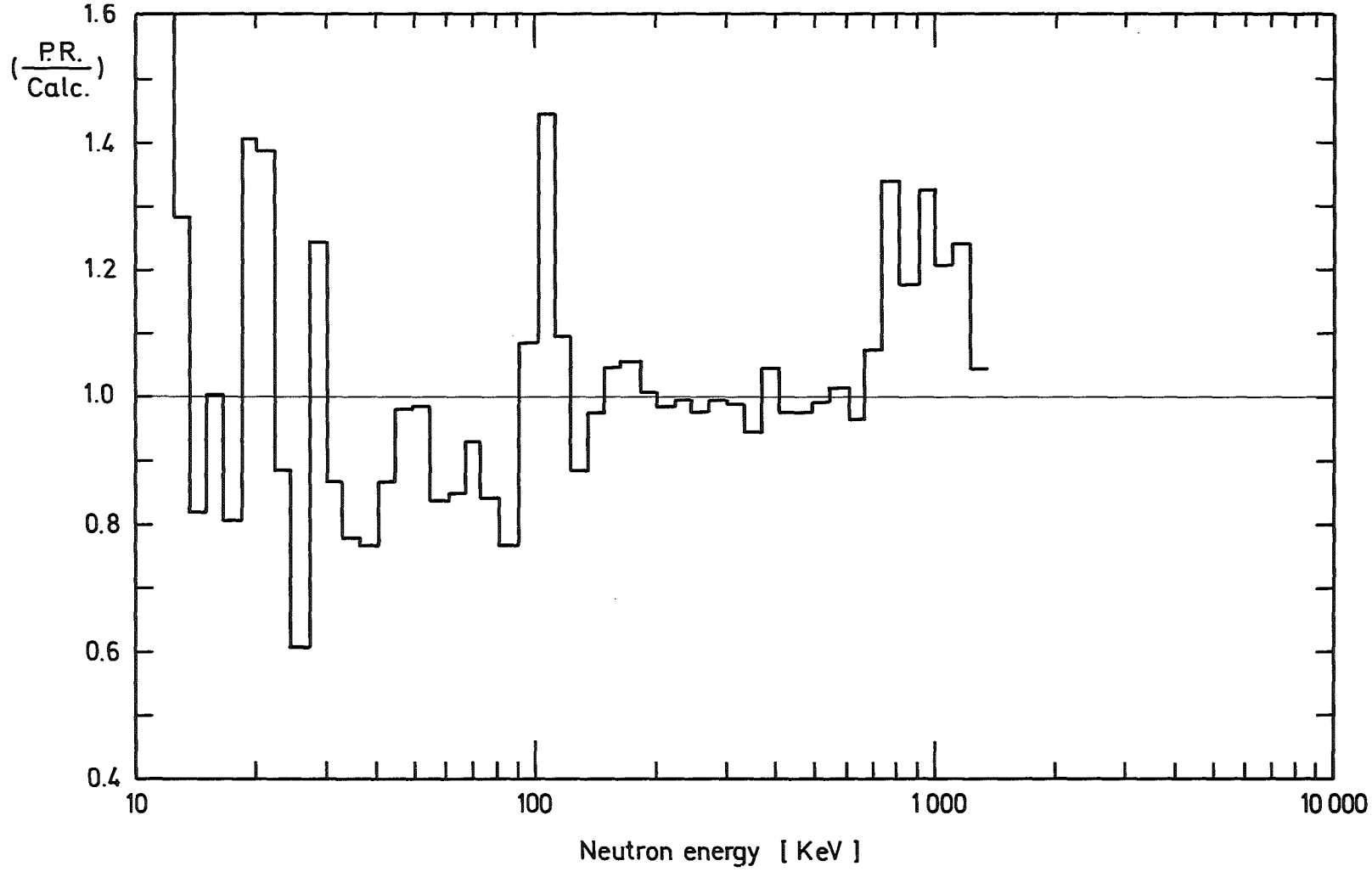
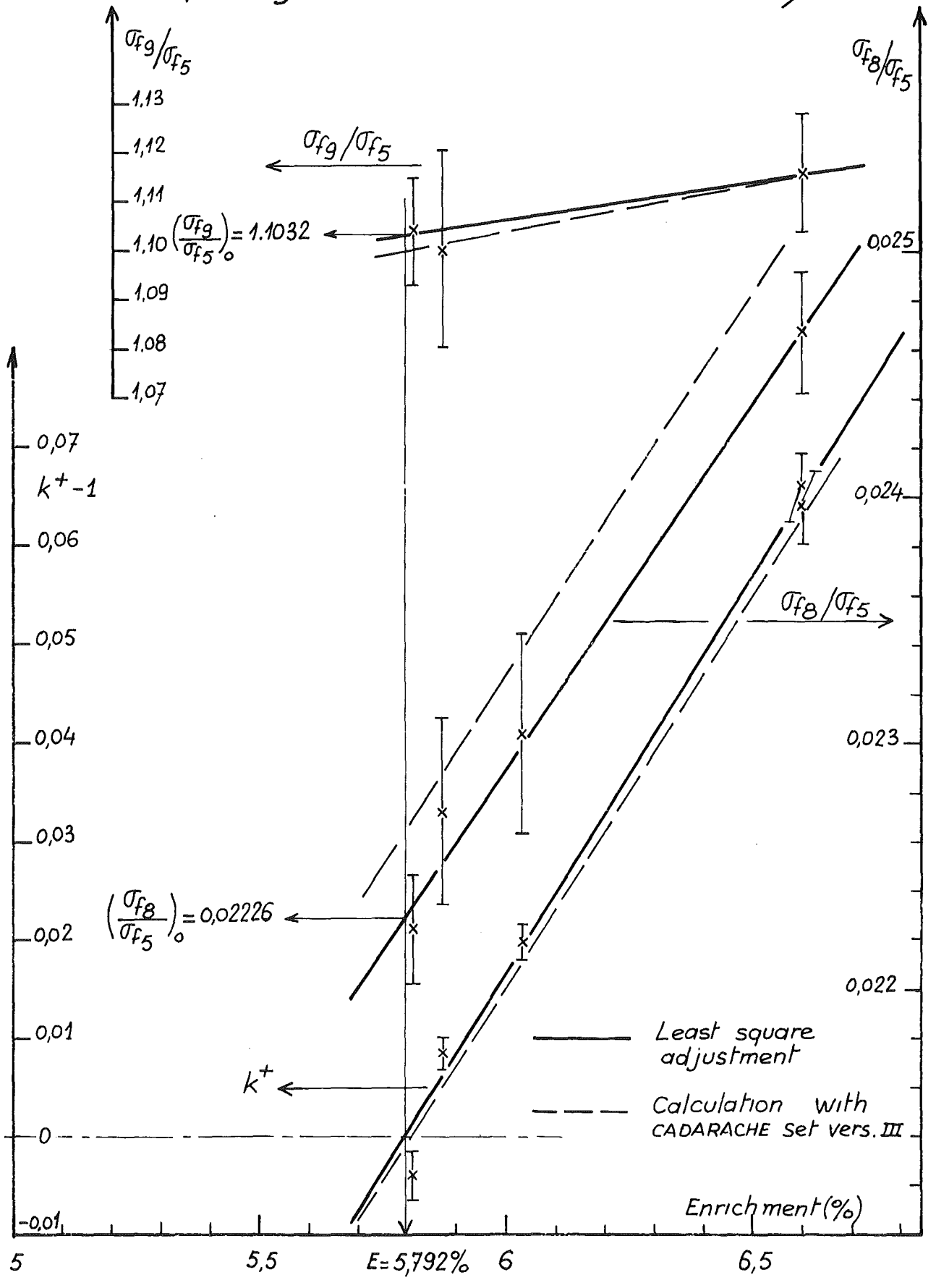


Fig. VII.3 UK 5 - HARMONIE.
Ratio of Measured and Calculated Spectrum (Kedak Data)

Fig. VIII-1 - REGRESSION METHOD

(Homogeneous medium with structure)



Appendix I

Atom densities for heterogeneous cell calculations in SNEAK, ERMINE and HARMONIE

The atom densities for the different platelets used in cell calculations in SNEAK-8 and 8Z are given in Table A-1. Note that the stainless steel of the tube was homogenized with the material of the platelet.

The atom densities used in heterogeneous cell calculations for UK 1, UK 2 and UK 5 are given in Table A-2. The stainless steel of the tube was homogenized with the depleted uranium.

Table A-1 Atom densities used in heterogeneous cell calculations for SNEAK-8 and 8Z, 10^{20} at/cm^3

Plate	U-20%	U-35%	U_{nat}	U_{dep}	C (driver zone)
Thickness of plate, cm	0.3150	0.3144	0.3134	0.1555	0.316
^{235}U	81.03	142.87	2.92	1.60	--
^{238}U	323.19	261.76	402.82	393.89	--
Cr + Mn	11.99	11.99	11.99	11.99	11.96
Fe	39.68	39.68	39.68	39.68	39.55
Ni	12.80	12.81	12.72	16.02	5.72
C	3.76	3.76	3.76	3.76	780.96
Mo + Nb	0.18	0.18	0.18	0.18	0.18
Si	0.45	0.45	0.45	0.45	0.45
H	0.18	0.18	0.18	0.18	--
Al	0.24	0.24	0.24	0.24	--

Table A-2 Atom densities used in heterogeneous cell calculations for UK 1, UK 2, and UK 5, 10^{20} at/cm^3

Lattice	UK 1		UK 2		UK 5	
	Zone 1	Zone 2	Zone 1	Zone 2	Zone 1	Zone 2
R (cm)	0.628	1.495	0.628	1.495	0.628	1.495
^{235}U	124.6	1.620	107.3	1.090	142.5	1.620
^{238}U	345.2	384.9	363.8	302.0	328.3	384.9
Fe	0.30	37.61	0.30	37.56	0.30	37.61
Cr	1.93	11.63	1.93	11.28	1.94	11.63
Ni	0.10	19.66	0.10	22.77	0.10	20.43
C	3.719	3.069	3.721	2.398	3.725	3.069
Cu	0.35	0.29	0.35	0.23	0.35	0.29
Al	0.37	0.31	0.37	0.24	0.37	0.31

Appendix II

Determination of the multiplication factor from the normalized worth of the unit cell

The relation (4-1), which is used in the PCTR technique to obtain the multiplication factors k_∞, k^*, and k^+ from the measured reactivity worth of the unit cell, will be derived and discussed in this Appendix.

The derivation of (4-1) involves three steps.

1) Correction of the measurements to the fundamental mode (FM)

The first step in the interpretation is to correct the measured central worth of the unit cell, normalized to the worth of ^{235}U, for the spectrum mismatch, or to convert it to the value for the FM.

One expects that the worth of ^{235}U is not appreciably influenced by a slight spectrum mismatch, whereas the cell worth, being a delicate balance between production and absorption effects, may be sensitive to slight distortions of the spectrum. However, it will be demonstrated that the latter dependence is only of second order in the real and adjoint flux mismatch.

The equation for the neutron flux in the zoned core is

$$- D(E)\nabla^2\Phi(E,r) + A\Phi(E,r) = \lambda P\Phi(E,r) \qquad (A-1)$$

where A and P are the operators for absorption and degradation, and for production, and λ is the eigenvalue.

The worth of the unit cell at the core center is given by

$$\delta k_{cell} = \frac{1}{N_c} \left[\lambda(\Phi^+, P\Phi) - (\Phi^+, A\Phi) \right] \qquad (A-2)$$

where the fluxes are taken at the core center.

One can split the fluxes in a FM flux, plus a flux mismatch $\delta\Phi$

$$\Phi(E,r) = \psi(E)g(r) + \delta\Phi(E,r) \qquad (A-3)$$

The equation for the FM spectrum $\psi(E)$ is

$$(DB^2 + A)\ \psi(E) = \lambda P\psi(E) \qquad (A-4)$$

and the core material worth in the FM is

$$\delta k^F_{cell} = \frac{1}{N_F} \left[\lambda(\psi^+, P\psi) - (\psi^+, A\psi) \right]$$

Then, one obtains from (A-2), (A-3) and (A-4) (with g(r) = 1 at the core center)

$$\delta k_{cell} = \frac{1}{N_c} \left[(\psi^+ D\psi) B^2 + (D\psi \delta\Phi^+) B^2 + (D\psi^+ \delta\Phi) B^2 + (\delta\Phi^+, \lambda P - A, \delta\Phi) \right] \qquad \text{(A-5)}$$

Furthermore, one can show that the orthogonality relation

$$\int \psi^+(E) D(E) \delta\Phi(E,r) dE = 0$$

holds. Thus, the first order terms in (A-5) vanish, and one has

$$\delta k_{cell} = \frac{1}{N_c} \left[N_F \, \delta k^F_{cell} + (\delta\Phi^+, \lambda P - A, \delta\Phi) \right] \qquad \text{(A-6)}$$

Equation (A-6) means that the central cell worth in a zoned core and in the FM differ (except for the normalization) only in second order in the mismatch of the real and adjoint flux spectra.

Furthermore, as the worth of ^{235}U depends certainly only weakly on the spectrum mismatch, one concludes that the normalized worth of the unit cell in the FM can be obtained by application of a small additive correction $\tilde{\varepsilon}$ to the measured worth in the zoned core

$$\left(\frac{\delta k_{cell}}{\delta k_{U5}}\right)_{FM} = \frac{\delta k_{cell}}{\delta k_{U5}} + \tilde{\varepsilon} \qquad (A\text{-}6)'$$

Numerical calculations show that $\tilde{\varepsilon}$ is indeed very small for all the assemblies covered in this report.

2) Determination of k^+ in the fundamental mode (FM)

In the second step, k^+ for the FM will be determined. With the following definition of k^+

$$k^+ = \frac{(\psi^+, P\psi)}{(\psi^+, A\psi)} \qquad (A\text{-}7)$$

one can write the cell worth as

$$\delta k^F_{cell} = \frac{1}{N_F} \cdot (\lambda k^+ - 1)\ (\psi^+, A\psi) \qquad (A\text{-}8)$$

The worth of ^{235}U is

$$\delta k^F_5 = \frac{1}{N_F} \left[\lambda (\psi^+, P_5\psi) - (\psi^+, A_5\psi) \right] \qquad (A\text{-}9)$$

where the operators P_5 and A_5 contain the cross sections of ^{235}U only. By combining (A-7), (A-8), and (A-9) one obtains

$$\lambda k^+ = 1 + m^+ \left(\frac{\delta k_{cell}}{\delta k_5}\right)_{FM} \qquad (A\text{-}10)$$

where

$$m^+ = \frac{\lambda(\psi^+, P_5\psi) - (\psi^+, A_5\psi)}{(\psi^+, A\psi)}$$

By combining (A-10) and (A-6)' one obtains the relation (4-1)

$$k^+ = 1 + m^+ \frac{\delta k_{cell}}{\delta k_{U5}} + \varepsilon^+, \qquad (4\text{-}1)$$

which relates k^+ to the measured cell worth. Note that the "experimental" λ is equal to one.

The relation (A-10) is very simple, because the coefficient m^+ is clearly defined by an analytic expression, and can be calculated by standard methods within a few percent. Thus, one finds that the cell worth measurements determine essentially the bilinearly weighted multiplication factor k^+, which is not surprising, as the reactivity worth is defined by an expression with bilinear weighting. One could in principle, stop at this point, and compare the experimental k^+ with calculated values. However, for comparison with the multiplication factor k_∞, which is calculated by the standard codes at GfK, and also for establishing the balance of reaction rates, one has to go one step further, and determine k_∞ and k^* from k^+.

3) Procedures used to determine k_∞ and k^*

The multiplication factors k_∞ and k^* are defined as

$$k_\infty = \frac{(1,P\psi_\infty)}{(1,A\psi_\infty)} \qquad k^* = \frac{(1,P\psi)}{(1,A\psi)} \tag{A-11}$$

where ψ is the solution of Eq. (A-4), and ψ_∞ is the solution of the "static mode" equation

$$A\psi_\infty(E) = \frac{1}{k_\infty} P\psi_\infty(E) \tag{A-12}$$

Different procedures are used at GfK, and at CEA to determine k_∞ and k^*.

At GfK, it is observed that the eigenvalue λ in Eq. (A-1) and (A-4) may be adjusted to reproduce the experimental cell worth, and therefore the buckling, correctly. This means that the neutron production is modified by the factor λ, and the factors k must be multiplied by λ, so that the experimental values are

$$k_\infty \text{ (exp)} = \lambda k_\infty, \qquad k^* \text{ (exp)} = \lambda k^*, \tag{A-13}$$

and one can write Eq. (A-12) as

$$A\psi_\infty(E) = \frac{\lambda}{k_\infty \text{ (exp)}} P\psi_\infty(E)$$

Then, the procedure used at GfK consists in performing the following calculations:

- Diffusion calculations in spherical geometry, with variable thickness of the driver zone, gives λ as a function of the normalized cell worth (Eqs. (A-1) and (A-2));

- Zero-dimensional calculations with variable B^2, give B^2 (Eq. (A-4)) and k^* (Eq. (A-11)) as a function of λ;

- Zero-dimensional calculation with $B^2 = 0$, gives k_∞ (Eq. (A-11)).

Thus, with λ determined from the cell worth, the k values are obtained from (A-13). The results, obtained with the MOXTOT set, are given in Section IV.3.1.

At CEA, the quantities k_∞ and k^* are derived from the cell worth $\frac{\delta k_{cell}}{\delta k_5}$, using a similar relationship:

$$k^* = 1 + m^* \frac{\delta k_{cell}}{\delta k_5} + \varepsilon^* \qquad \text{(A-14)}$$

$$k_\infty = 1 + m_\infty \frac{\delta k_{cell}}{\delta k_5} + \varepsilon_\infty \qquad \text{(A-15)}$$

The analytic expressions of the quantities m_∞ and m^* are more complicated than for m^+.

Using the equations (4-1), (A-14) and (A-15) we obtain

$$m_\infty = \frac{k_\infty - 1}{k^+ - 1} \cdot m^+ = \frac{(\psi^+_\infty, D\psi_\infty)}{(\psi^+, D\psi)} \cdot \frac{\delta k_5}{(\psi_\infty, A\psi_\infty)} \qquad \text{(A-16)}$$

$$\varepsilon_\infty = \frac{k_\infty - 1}{k^+ - 1} \varepsilon^+ \qquad \text{(A-17)}$$

and similar relations for m^* and ε^*.

The variation of the ratios m^*/m^+ is given in Table A-3 for different lattices (homogeneous calculations) using the two Cadarache sets (both sets give the same values).

Table A-3

	UK 1	SNEAK-8	SNEAK-8Z	UK 5
$\frac{m^*}{m^+}$	1.31	1.31	1.30	1.29

The influence of the cross section set on this ratio is shown in Table A-4 for SNEAK-8.

Table A-4

	MOXTOT	CAD II	CAD III
m^+	0.45	0.45	0.45
$\frac{m^*}{m^+}$	1.27	1.30	1.30

The calculated values for m and ε are given in Section IV.3.1.

Appendix III

Influence of a flux gradient on the worth of the unit cell

In order to determine k_∞ from the worth of the unit cell, one needs to know the worth at a location in the core where the flux gradient is zero. In practice this condition is not easy to achieve, and even a slight asymmetry in the driver may lead to undesirable flux gradients at the geometrical core center. Therefore, it is necessary to calculate the influence of a flux gradient on the unit cell worth, and in some cases, corrections to the experimental data are necessary.

These corrections are calculated in a one group approximation.

The reactivity worth of a local change in composition is given in diffusion theory, using the first order perturbation, by the expression

$$\delta k = \frac{1}{N_c} \left[\int \Delta\nu\Sigma_f \Phi\Phi^+ dV - \int \Delta\Sigma_a \Phi\Phi^+ dV + \int \Delta D \text{ grad } \Phi \text{ grad } \Phi^+ dV \right]$$

In case the change in composition consists in removing cell material, one has $\Delta\nu\Sigma_f = -\nu\Sigma_f$, $\Delta\Sigma_a = -\Sigma_a$, and in first

approximation $\Delta D = - D$ (where $\nu\Sigma_f$, Σ_a and D are the production cross section, the absorption cross section, and the diffusion coefficient of the cell).

The one-group diffusion equation reads

$$D\Delta\Phi + (k_\infty - 1)\ \Sigma_a\ \Phi = 0$$

In cylindrical geometry assuming that there is no asymmetry in the driver the solution of this equation is

$$\Phi(\vec{r}) = \Phi_o \cos \alpha z\ J_o\ (\beta r)$$

The corresponding adjoint flux is given by

$$\Phi^+\ (\vec{r}) = \Phi_o^+ \cos \alpha z\ J_o\ (\beta r).$$

The worth of the unit cell at a position r,z in the core is, besides a normalization factor, given by the expression

$$\delta k_{cell} = (k_\infty - 1)\ \Sigma_a\ \Phi\Phi^+ + D\ \text{grad}\ \Phi\ \text{grad}\ \Phi^+$$

which may be written

$$\delta k_{cell} = - D \left[\alpha^2\ J_o^2\ (\beta r) + \beta^2 \cos^2 \alpha z\ (J_o^2\ (\beta r) + J_1^2\ (\beta r)) \right]$$

The worth of ^{235}U, which is used for normalization, can be written approximately:

$$\delta k_5 = (\nu\Sigma_{f5} - \Sigma_{a5}) \cos^2 \alpha z \, J_o^2 (\beta r)$$

and the final expression used is then:

$$\frac{\delta k_{cell}}{\delta k_5} = - \frac{D (\alpha^2 + \beta^2 \cos^2 \alpha z (1 + \frac{J_1^2}{J_o^2} (\beta r)))}{(\nu\Sigma_{f5} - \Sigma_{a5}) \cos^2 \alpha z} .$$

In SNEAK, a slight axial flux gradient was present in the standard core SNEAK-8. From the fission rate traverses (Appendix IV.), one estimates that the relative flux slope in axial direction at the position of the measurement (the geometric core center) is 0.001 cm^{-1}. Then, from the equation above, the normalized worth of the unit cell should be 1% larger than at the position of zero gradient. This estimate is consistent with the measurements in the standard core, and in the clean core of SNEAK-8. In SNEAK-8Z, the gradient was even smaller.

In ERMINE, it was necessary to apply corrections for the flux gradient because of the small height of the core and the more important asymmetrics of the thermal zone loading. The corrections were determined in the following way.

In the central zone we assumed that the flux and the adjoint flux may be written

$$\Phi(\vec{r}) = \Phi_o \, X(x) \, Y(y) \, Z(z)$$

$$\Phi^+(\vec{r}) = \Phi_o^+ \, X(x) \, Y(y) \, Z(z)$$

where

$$X(x) = A \, e^{-\gamma x} + (1 - A) \, e^{\gamma x}$$

$$Y(y) = C \, e^{-\gamma y} + (1 - C) \, e^{\gamma y}$$

$$Z(z) = \cos B_z \, z.$$

B_z was obtained from axial fission rate traverses (Appendix IV.)

γ^2 was calculated from the relation

$$2\gamma^2 + B_z^2 = B_T^2$$

where B_T^2 is the calculated buckling of the test zone.

A and C were obtained from radial fission rate traverses (Appendix IV.).

The correction due to the axial curvature of the flux is about 0.2% $\frac{\delta k}{k}$ for a cavity of 101.6 mm height.

It was tested in a different lattice studied in ERMINE.

The radial correction is principally due to the asymmetry of the thermal zone loading. It was about 0.2% $\frac{\delta k}{k}$ in UK 1 and 0.4% $\frac{\delta k}{k}$ in UK 5 and was tested in UK 1 (Table IV-2).

Appendix IV

Additional experiments

1) Fission chamber traverses in SNEAK-8

The fission chamber traverses with ^{235}U and ^{238}U in axial and radial direction were measured in order to detect any asymmetry in the core flux, and to check whether the spectral index σ_{f8}/σ_{f5} did not vary much in the region where the cell worth measurements were performed. Also, the traverses demonstrate that the spectral index is almost twice as large in the driver zone than in the test zone.

The results are shown in Fig. A-1 and A-2. The axial traverses in the slightly supercritical standard core show a slope, which is about 0.1% per cm. According to Appendix III, this influences the normalized unit cell worth only negligibly. In the clean core, the slope is smaller, but still detectable. The spectral index varies only about 1% in the region where the cell worth measurements were made, that is between - 10 cm and + 10 cm. The radial traverses show only a negligibly small slope.

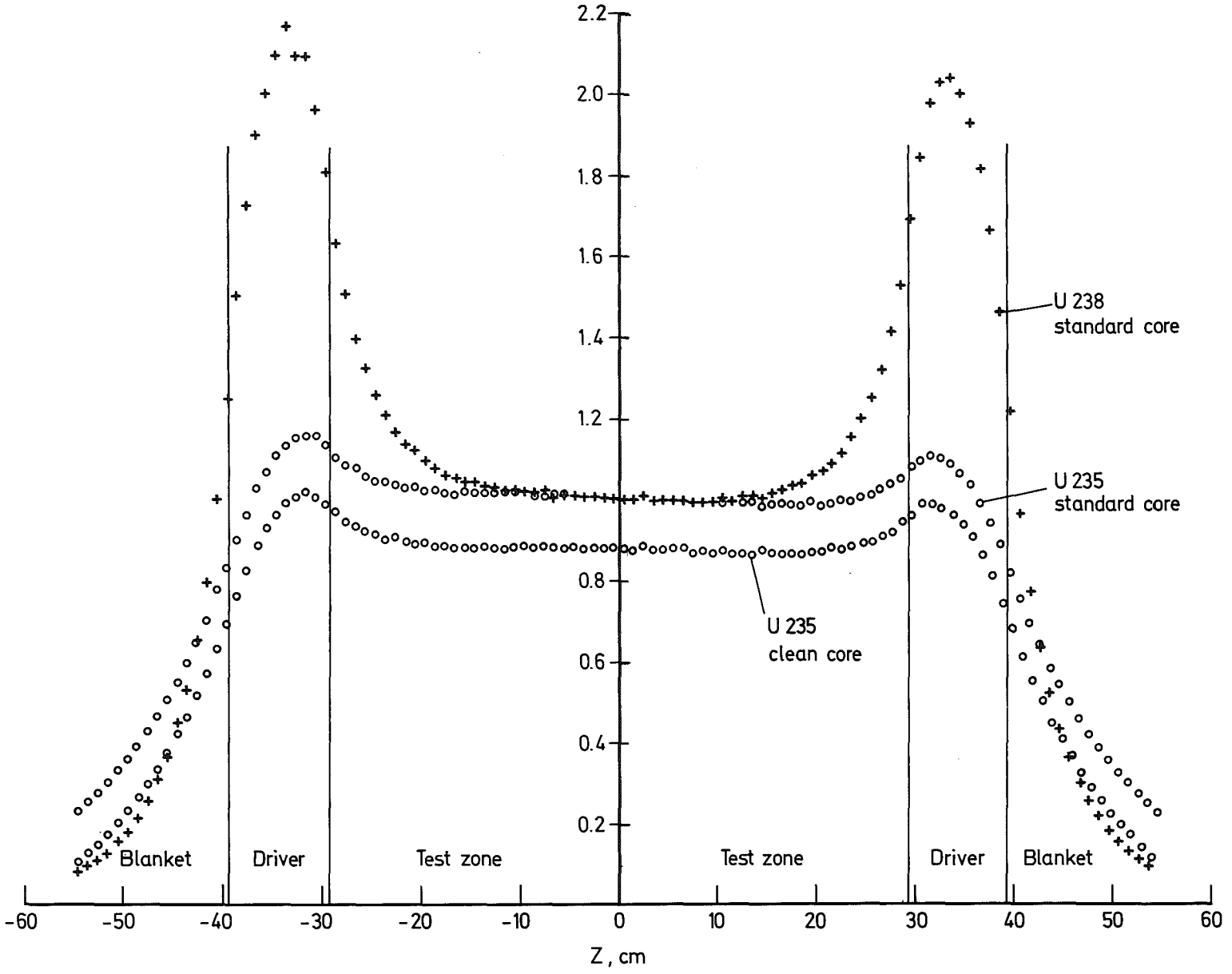


Fig. A-1 Axial fission rate traverses in SNEAK-8

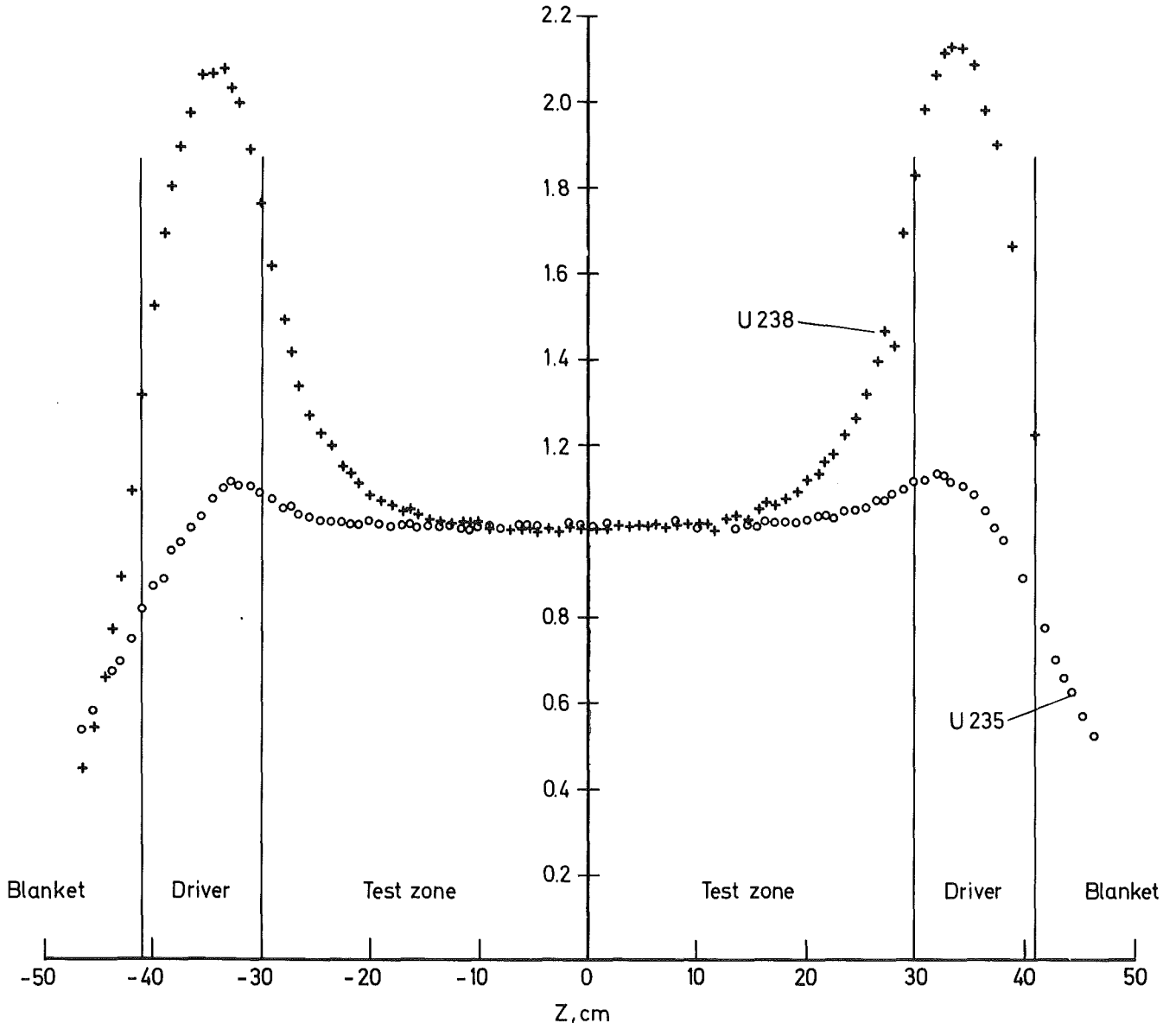


Fig. A-2 Radial fission rate traverses in SNEAK-8

2) Central reactivity worth measurements with the pile oscillator in SNEAK-8

The central reactivity worths of several important isotopes were measured with the pneumatic pile oscillator in SNEAK-8. The samples had the shape of platelets, with a cross section of 4.6 x 4.6 cm^2. They were inserted into the regular test zone lattice, which constituted the loading of the oscillator element. Most samples were measured between two natural uranium platelets of the cell, against an aluminium frame as reference. The inverse kinetics method was used to obtain the reactivity worths.

The reactivity worth calculations were performed using first order perturbation theory, following a diffusion calculation in spherical geometry. The results were improved in two ways. First, the values were normalized to a two-dimensional diffusion calculation in R-Z-geometry with the code DIXY. Second, for some samples, calculations with the KAPER code were carried out, which accounts for the heterogeneity of the sample and its environment. The cross section set KFKINR was used; the calculated value of β_{eff} is 0.0070.

The results are gathered in Table A-5. The calculated heterogeneity corrections in the last column are negligibly small, except for ^{10}B and SS.

The calculated worths of the fuel isotopes agree well with the experiment, except for ^{240}Pu, which is highly overestimated. On the other hand, ^{10}B is largely underestimated. Thus, the high-energy cross sections of the latter two isotopes are probably in error. The worths of the structural materials are all overestimated, which may be due to uncertainties in the inelastic scattering data. Note

Table A-5 Material worths at the core center of SNEAK-8

Sample	Sample weight, g	Measured worth, 10^{-6} \$/g	Calc./Exp.	Calc. Difference $\frac{\text{Hom} - \text{Het}}{\text{Hom}}$
^{235}U	6.7	167.1 ± 2%	1.000	- 0.0008
	10.4	167.9 ± 1.5%	0.996	- 0.0018
	13.7	167.6 ± 1%	0.999	- 0.0027
^{238}U in U_{nat}	125	-9.68 ± 1.5%	1.013	+ 0.004
in U_{dep}	123	-9.56 ± 2%	1.026	+ 0.004
^{239}Pu	4	256 ± 3%	0.968	- 0.005
^{240}Pu	3	29 ± 20%	1.72	
^{241}Pu	1.5	284 ± 6%	1.032	
^{10}B	0.30	-1945 ± 4%	0.803	+ 0.010
	0.59	-1953 ± 2%	0.792	+ 0.020
SS	109	-10.0 ± 4%	1.156	0.050
SS[a)]	109	- 8.0 ± 5%	1.271	0.164
Al	28	-18.8 ± 5%	1.28	--
Fe	102	- 8.25± 6%	1.28	
Ni	115	-12.6 ± 4%	1.08	
O_2 (in Al_2O_3)	24.6	-47.5 ± 4%	0.89	

a) surrounded by 4.5 mm SS

that the adjoint spectrum at the center of SNEAK-8 shows a strong increase above the fission threshold of ^{238}U. Therefore, this assembly is suitable to emphasize the inelastic degradation of material worth samples, and indeed, the contribution of degradation to the worth of the structural materials is rather large (75% for SS, 78% for Fe, 92% for Al, 57% for Ni). The measurements indicate that the inelastic scattering cross sections of these materials are too large.

In order to study the effect of environment on the SS worth, a measurement with a sample surrounded by 4.5 mm SS was carried out, in addition to the one in the standard cell. The decrease in worth by the SS environment is in principle predicted by calculation, though the fairly large errors do not allow accurate quantitative conclusions.

3) Fission traverses in ERMINE

Axial traverses in ERMINE UK 5

The fission rate traverses were measured with ^{235}U chambers, and with enriched and depleted uranium foils. The results are given in Fig. A-3. The index σ_{f8}/σ_{f5} did not vary much over a height of 20 cm.

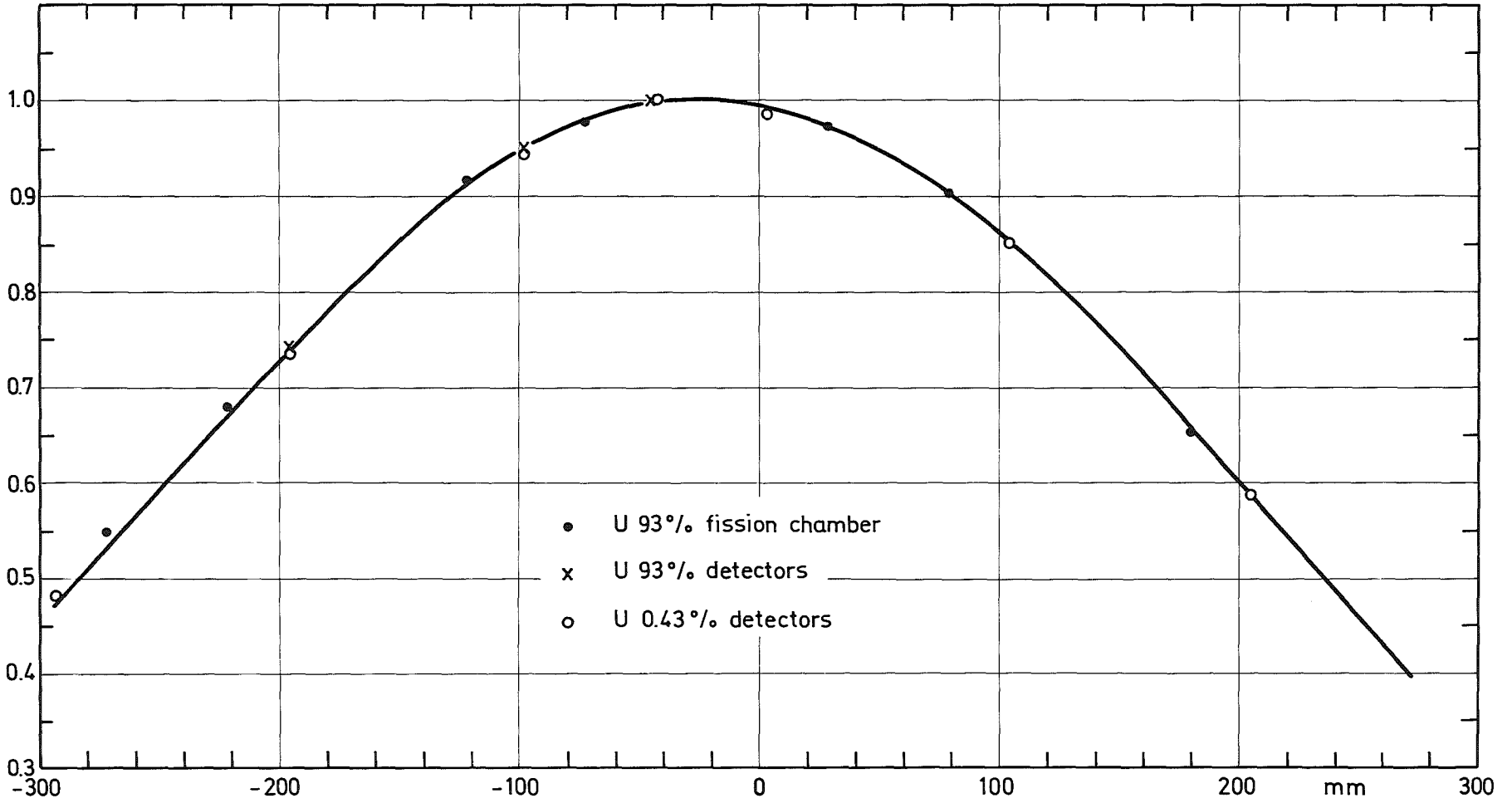
Radial traverses in ERMINE UK 1 and UK 5

They were measured with 93% enriched and 0.43% depleted uranium foils, in two perpendicular directions. The results for different driver configurations are shown in the Fig. A-4, A-5, A-6. The results obtained for UK 1 and UK 5 with the same loading of the thermal zone are given in the same figure. The accuracy in relative values is about 0.5% (one σ confidence interval) for the measurements with enriched uranium foils and 1% for the measurements with depleted uranium foils.

Within the measurement zone (- 26.5 mm to + 26.5 mm) the index σ_{f8}/σ_{f5} was nearly constant.

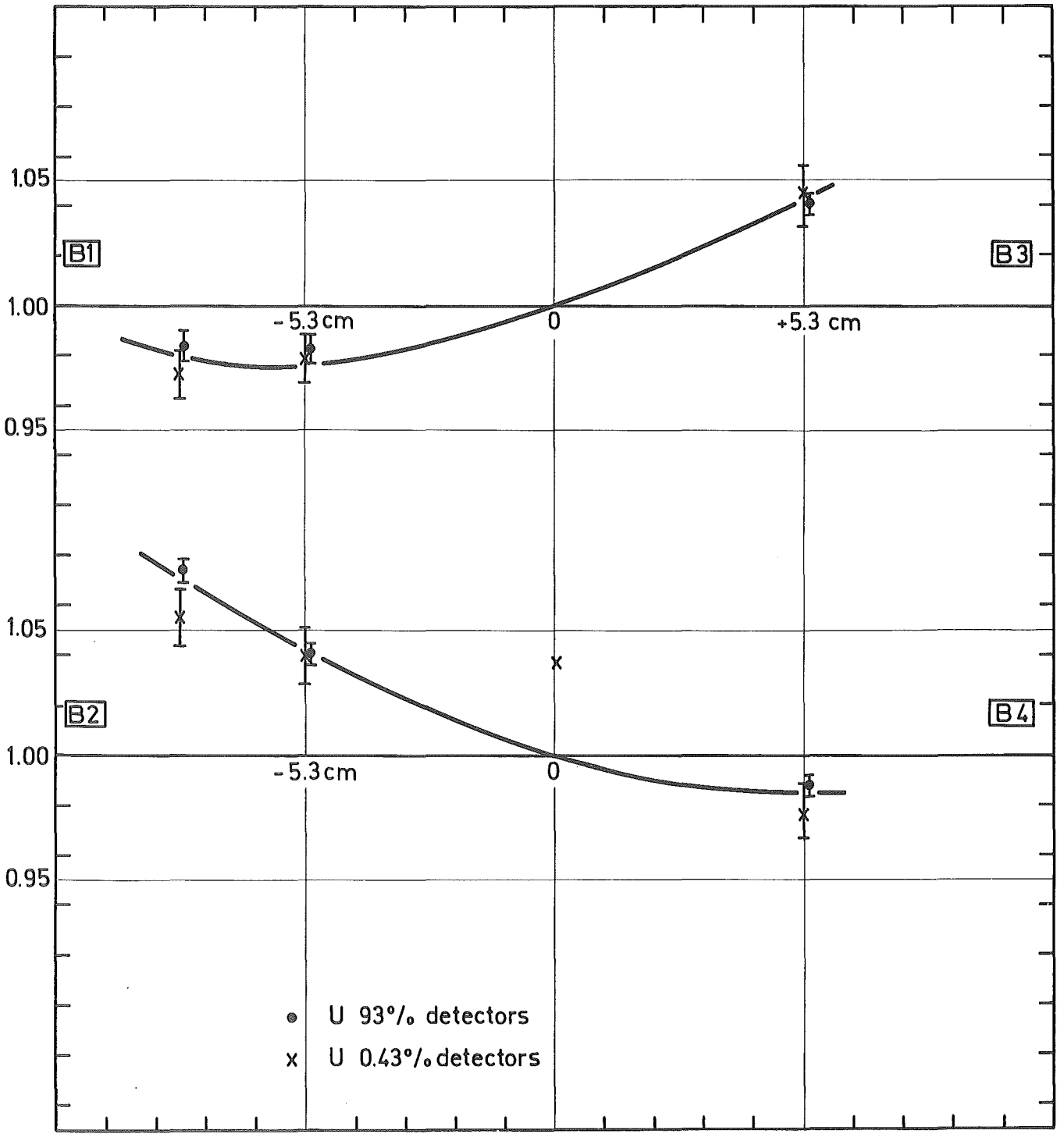
Axial traverses UK 5

Fig. A3



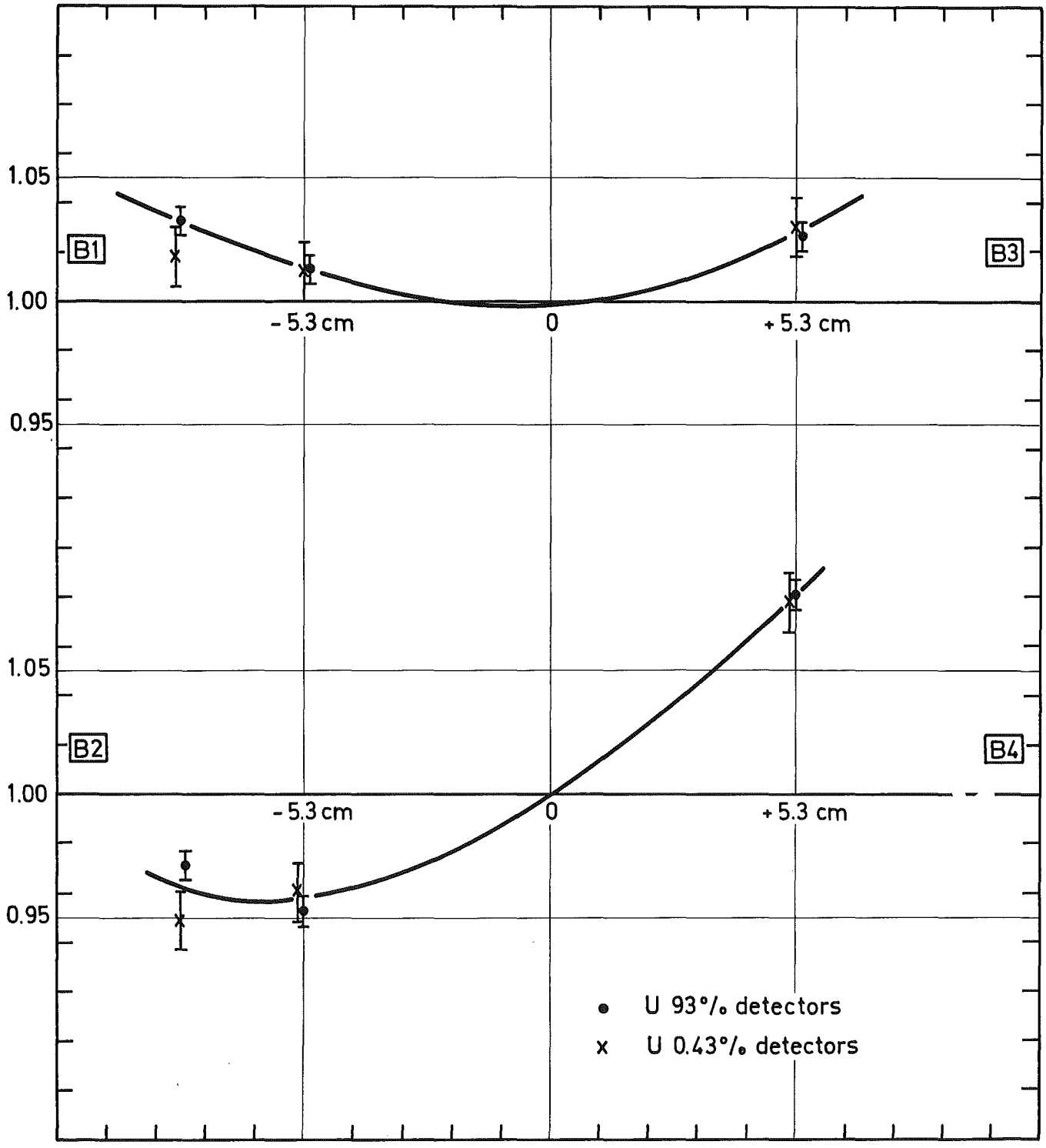
Radial traverses UK5 - UK1

Fig. A4 - First thermal zone configuration



Radial traverses UK 1

Fig. A5 - Second thermal zone configuration



Radial traverses UK 1

Fig. A6 - Third thermal zone configuration