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STUDIES OF UNIT K∞ LATTICES IN METALLIC URANIUM ASSEMBLIES ZEBRA 8H, SNEAK 8, ERMINE AND HARMONIE UK

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ABSTRACT

Following the proposal of U.K.A.E.A. to the E.A.C.R.P., experimental lattices consisting of metallic uranium with minimum diluents and with enrichments such that k_∞ (production/absorption) is close to unity have been studied in Winfrith, Karlsruhe, Fontenay aux Roses and Cadarache. After analysis of the methods developed for the derivation of k_∞ from measurements of cell reactivity worth or buckling, the experimental results are compared with the values calculated by the standard method of each laboratory. Finally, all the experimental results are combined, to determine the values of the enrichment and reaction rate ratios of a homogeneous uranium medium of exactly unit k_∞ : " SCHERZO 556 " core - This medium is proposed as an international standard for nuclear data tests.

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1. INTRODUCTION :

A proposal that a metallic uranium lattice with k-infinity of unity be adopted as a standard reference medium which would be closely represented using components available at all fast reactor laboratories was discussed at the 1970 meeting of EACRP. Such a standard would facilitate intercomparison of experimental techniques and the combined results obtained would provide accurate integral parameters for testing U235 and U238 cross section data.

Lattices of this type have now been studied in France (Ermine UK1, UK5, Harmonie UK5), West Germany (Sneak 8, 8Z),Japan (FCA4-1), United Kingdom (Zebra 8H) and United States (ZPR9-25). This paper outlines the studies in the three European countries. The results of these are combined to define the parameters of a pure homogenous uranium medium of exactly unit k-infinity which are compared with predictions using three fast reactor data sets.

2. DESCRIPTION OF THE ASSEMBLIES :

2.1. Unit cells of the test region :

The five lattices studied were built with metallic uranium plates or rods loaded into stainless steel tubes.

The main characteristics and the composition of the different cells are summarized in tables I and II.

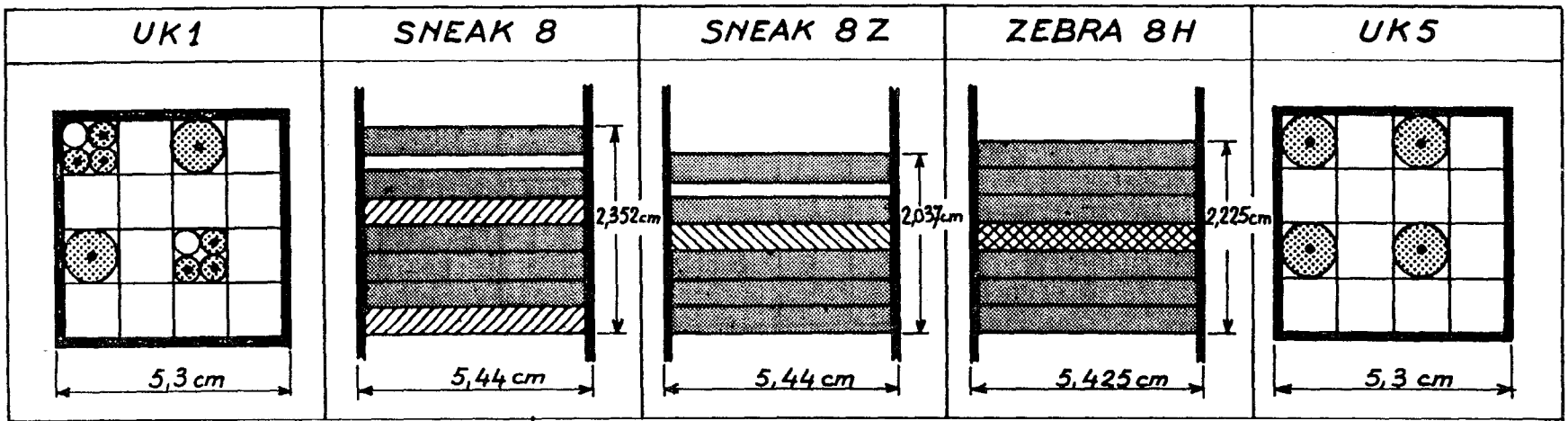
TABLE I : MAIN CHARACTERISTICS OF TEST REGION CELLS

Lattices	UK1	SNEAK 8	SNEAK 8Z	ZEBRA 8H	UK5
Materials	RODS	PLATES	PLATES	PLATES	RODS
Mean enrichment (in a/O)	5,81	5,87	6,03	6,08	6,60
$\frac{\text{Structure mass}}{\text{Uranium mass}}$	0,032	0,038	0,038	0,026	0,032

The ZEBRA 8H assembly was studied first [17]. The cell was chosen to give a predicted k-infinity value close to unity while at the same time retaining a fairly simple arrangement to ease the calculational problems.

The availability of results from ZEBRA 8H was a great help in the design of the SNEAK cells. The unit-cell of SNEAK 8Z matched the unit cell of 8H as closely as possible while the unit cell of SNEAK 8 was designed to obtain a k-infinity closer to unity with a reasonable cell height [2].

T A B L E II. - TEST REGION CELLS.



Dimensions of the rods and plates

UK rods : - circular cross section Ø.635 cm and Ø 1.27 cm

- square cross section 1.27 x 1.27 cm^2

SNEAK plates: - square cross section 5.077 x 5.077 cm^2

- thickness .314 cm and .157 cm

ZEBRA plates: - square cross section 5.06 x 5.06 cm^2

- thickness .3175 cm

N.B : All the uranium components are coated with nickel, except the Zebra plates -

The very simple UK5 unitcell allows a good interpretation of reaction rate ratios and heterogeneity measurements : the UK1 unit cell is fairly complicated but k-infinity is very close to unity [27].

2.2. Design of the critical cores :

Three types of assembly were studied :

a) critical experiments ZEBRA and SNEAK :the test region was large ; criticality was achieved with a driver region of high reactivity, both radially and axially.

b) thermal fast critical assembly ERMINE :the small test region was fed radially by a thermal core ; a transition zone converted the thermal neutron flux into a central spectrum as close as possible to the fundamental mode spectrum.

c) exponential experiment :the test region was placed vertically above the HARMONIE core.

The test region volumes and the main characteristics of the assemblies are shown in table III.

Remarks:

a) ERMINE UK1:only half of the test region (25,7 ℓ) was constructed from UK1 lattice . The other part was built using cells with an enrichment and k-infinity very close to those of UK1 cells, but with a lower density.

b) SNEAK 8Z: the SNEAK 8Z lattice was loaded only as an inner zone of 45 liters ; the rest of the test region had the composition of SNEAK 8.

c) HARMONIE UK5:the exponential assembly is a prism of 53 x 53 cm^2 square cross section and 90 cm height.

TABLE III : MAIN CHARACTERISTICS OF ASSEMBLIES .

	ERMINE UK1	SNEAK 8	SNEAK 8Z	ZEBRA 8H	ERMINE UK5	HARMONIE UK5
Volumes (ℓ)	52	190	190	157	52	285
Driver	thermal zone + radial adapta-tion zone	U 35% + C axiall and radially		U93%+C axially and radially	thermal zone + radial adapta-tion zone	Harmonie core

3. NOTE ON THE CALCULATIONAL METHODS AND CROSS SECTION SETS

3.1. Cross section sets : the final calculated results reported in this paper were obtained with the cross-section set used in each laboratory at the present time : FGL 5 [3], KFKINR [4], and Version III Cadarache set [5]. The experimental design and analysis were in some cases made with earlier versions.

3.2. Cell codes : the integral parameters of the unit cells were calculated with MURAL [6], KAPER and ZERA [7], and HETAIRE [5].

3.3. Spatial calculations : One-dimensional diffusion theory in spherical geometry was used to calculate the SNEAK and ZEBRA assemblies, since previous experience had shown that this approximation was satisfactory. The spatial calculations of the thermal fast assembly ERMINE were performed in cylindrical geometry with axial leakage using a one-dimensional transport theory. A very small correction was applied in order to take into account the difference between one-and two-dimensional calculations. The HARMONIE calculations were performed using one-dimensional transport theory ; the validity of these results was tested by comparison with two-dimensional transport calculations.

4. DETERMINATION OF K_∞ AND K^+ :

4.1. Principles of methods : The multiplication factors k_∞ and k^+ are defined starting from the balance equation in the fundamental mode :

a) with leakage :

$$(P-K)\,\phi = D\,B^2\,\phi \qquad (4\text{-}1)$$

D = diffusion coefficient

P = production operator

K = absorption and slowing-down operator

The multiplication factor k^+ is then defined as follows :

$$k^+ = \frac{\langle \phi^+, P, \phi \rangle}{\langle \phi^+, K, \phi \rangle} \qquad (4\text{-}2)$$

where ϕ^+ is the fundamental adjoint flux.

b) without leakage :

$$\left(\frac{P}{k_\infty} - K\right)\phi_\infty = 0 \qquad (4\text{-}3)$$

whence we obtain the multiplication factor k_∞ :

$$k_\infty = \frac{P\phi_\infty}{K\phi_\infty} \qquad (4\text{-}4)$$

The multiplication factors k (k^+ or k_∞) in a zone where k_∞ is very close to unity were obtained by measuring the residual leakage (k - 1) in the cell. Two methods were used :

a) Reactivity measurements :

Using first-order perturbation theory one can obtain the relationship between the test region k^+ and the reactivity worth (δk cell) of a central cell relative to the worth (δk_5) of the U235

content of the cell: the worth of U235 is not appreciably sensitive to slight distortions of the spectrum. This relationship is of the form :

$$k^+ = 1 + m^+ \frac{\delta k_{cell}}{\delta k_5} + \varepsilon^+ \qquad (4\text{-}5)$$

where m^+ et ε^+ must be calculated ; ε^+ is a small correction for the spectrum mismatch due to the influence of the driver zone and m^+ is defined by :

$$m^+ = \frac{\delta k_5}{\langle \phi^+, K, \phi \rangle}$$

A similar relationship may be obtain between k_∞ and $\frac{\delta k_{cell}}{\delta k_5}$

$$k_\infty = 1 + m^\infty \frac{\delta k_{cell}}{\delta k_5} + \varepsilon^\infty \qquad (4\text{-}6)$$

The quantities m^∞ and ε^∞ are analogous to m^+ and ε^+, but the analytic expressions are more complicated.

Note also, that the values of k^+ and k_∞, in this range of enrichment (k_∞ close to unity), are practically identical.

m^+, m^∞, ε^+ and ε^∞ show a small dependence on the nuclear data and the method of calculation.

b) Buckling measurement:

The multiplication factor k^+ is obtained from material buckling measurements using the calculated value of migration area M^{+2} corresponding to (4-1) :

$$K^+ = 1 + M^{+2} B_m^2 \qquad (4\text{-}7)$$

$$\text{with } M^{+2} = \frac{\langle \phi^+, D, \phi \rangle}{\langle \phi^+, K, \phi \rangle}$$

4.2. Measurement of the unit cell reactivity :

4.2.1. Methods of measurement : The worth measurements were made, in ZEBRA and SNEAK, by balancing the reactor at power using a fine control rod. In ERMINE, the oscillation technique was used : an automatic control-rod compensated the reactivity variations.

4.2.2. Unit cell reactivity :

It was not possible to measure directly the reactivity of the unit cell. The cell worth was obtained separately from the worth of the plates or rods and the worth of the associated steel sheath.

a) Reactivity of the core material : this was obtained by creating a cavity of variable size in the center of the test region. In order to support the core material above the cavity,special tubes (SNEAK), or thin-walled spacers of steel (ZEBRA) or aluminium (ERMINE) were used, a correction being applied for the reactivity contribution of the spacers.

b) steel sheath and spacer piece reactivity:

This was obtained from measurements with steel or aluminium samples of various geometries inserted into the space left by removal of the core materials.

As an example table IV gives the results obtained in ZEBRA 8H for different steel samples.The reactivities are expressed relative to the reactivity of U235 in the cell. Note that the uncertainties quoted here and throughout this paper correspond to one standard error(1σ).

TABLE IV : REACTIVITY WORTH OF STEEL IN ZEBRA 8 H -

N° of cells	Wall thickness of square section tube	Measured value per cell
2	2 mm	- 0.027 ± 0.003
2	0,76 mm	- 0.030 ± 0.002
18	0.76 mm	- 0.026 ± 0.002

c) Normalization :

All the reactivity worth measurements were related to the worth of the U235 content of the cell. The U 235 worth was found by replacing enriched uranium plates by natural uranium plates (ZEBRA,SNEAK) or by replacing 30 % enriched uranium rods by rods of lower density or enrichment (ERMINE)

d) Results:

The uncorrected experimental results may be written:

$$\left(\frac{\delta k_{cell}}{\delta k_5}\right)_{uncorrected} = \frac{\delta k_{cavity}}{\delta k_5} - \frac{\delta k_{spacers}}{\delta k_5} + \frac{\delta k_{tubes}}{\delta k_5} \quad (4\text{-}8)$$

4.2.3. Additional corrections :

Three corrections were applied to the experimental value given by the relation (4-8), in order to obtain : $\delta k_{cell}/\delta k_5$

a) Correction for the plate composition :

The core material reactivities were corrected for the differencesin weight between the material used in the experiment and the average of the test region. These corrections, generally very small, were obtained by measuring the reactivity worth of the cell components.

b) Correction for the flux gradient :

In order to determine k_∞ from the worth of the core materials, 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. It is therefore necessary to evaluate, by experiment or calculation, the correction due to the possible flux gradient.

In ZEBRA and SNEAK, this effect is slight and the estimate of it for ZEBRA was checked by building a modified version with an asymmetric driver region. In ERMINE, on the other hand, it is greater because the core height is small and the symmetry in the radial thermal zone is obtained with difficulty.The experimental reaction rate traverses were used to calcultate these corrections. The radial component was experimentally tested in UK1 by measuring for 3 thermal zone configurations. The results are given in table V.

TABLE V : FLUX GRADIENT CORRECTIONS IN ERMINE UK1

configuration		1	2	3
$\frac{\delta k_{cell}}{\delta k_5}$	uncorrected	0.0116 ± 0.0027	0.0217 ± 0.0030	0.0010 ± 0.0027
	corrected	- 0.0050 ± 0.0037	- 0.0050 ± 0.0050	- 0.0082 ± 0.0030

c) Correction of heterogeneity :

The reactivity worth of the cell may be dependent on the size of the cavity. This perturbation was found important in soft spectrum systems with " $k_\infty = 1$ ". It was mostly due to changes in the resonance self shielding in the uranium surrounding the cell removed. One would expect for our hard spectrum systems, that the dependence of the cell worth on the size of the cavity would be very small.
It is apparent from the experimental results that there is no significant variation in cell worth with the size.
One example is given in table VI for SNEAK-8Z.

TABLE VI : REACTIVITY WORTH OF CELLS IN SNEAK 8Z.

Number of tubes used	Number of cells removed	Worth of a plate cell $\frac{\delta k_{cavity}}{\delta k_5}$
4 tubes	3	.0762 $\pm$. 0025
	7	.0764 $\pm$. 0014
	10	.0767 $\pm$. 0010
9 tubes	3	.0734 $\pm$. 0018
	7	.0743 $\pm$. 0008
	10	.0747 $\pm$. 0008

4.3. Experimental buckling evaluation:

Fission rate distributions were measured in the exponential experiment UK5 with fission chambers (U 235, Pu 239, Np 237, U 238) in one vertical and three horizontal channels.

The vertical channel was placed close to the axis of the assembly.

The horizontal channels were positioned at about 30, 40 and 50 cm from the base. All these channels were introduced by removing depleted uranium.

The method used to obtain the relaxation constant and the radial cosine distribution at the different positions is described in [87].

4.4. Experimental results for k^+ and k_∞:

4.4.1. Determination of the multiplicetic : factors from the worth of core meterial.

a) Methods : The first method yields the multiplication factors k^+ in the fundamental mode with leakage, using the above mentioned relation (4-5). m^+ was calculated, starting from the analytic expression, ε^+ was deduced directly from the comparison between spatial and fundamental mode calculations.

The second method gives the multiplication factors k_∞, using the relation (4-6), in the static mode without leakage. m^∞ and ε^∞ were not directly calculated, but deduced from the calculated line relating k-infinity and cell worth. This line was obtained by modifying the $\bar{\nu}$ value of the test zone in the spatial calculations.

Table VII gives the m and ε values for the five lattices.

TABLE VII : CALCULATED VALUES OF m AND ε

	UK1	SNEAK 8	SNEAK 8Z	ZEBRA 8H	UK5
Data set	CAD	KFK	KFK	FGL	CAD
m^+	0.43	0.45	0.46		0.46
ε^+	0.0001	0.0002	-0.0002		0.0010
m^∞	0.43	0.45	0.46	0.45	0.46
ε^∞	0.0001	0.0002	-0.0002	0.0004	0.0010

b) Estimated errors :

The accuracies of k_∞ and k^+ measurements for the different assemblies are summarized in table VIII.

TABLE VIII : ERROR CONTRIBUTIONS TO K-MEASUREMENTS (% UNCERTAINTY IN K)

Source of error	UK1	SNEAK 8	SNEAK 8Z	ZEBRA 8H	UK5
material measurement	0.04	0.04	0.08	0.05	0.07
spacer measurement	0.09	-	-	0.15	0.09
sheath measurement	0.07	0.07	0.07		0.07
cell composition	0.15	0.05	0.05	0.05	0.05
impurities *	0.10	0.10	0.10	0.10	0.10
flux asymmetry	0.06	0.02	0.02	0.03	0.10
m	0.02	0.03	0.09	0.15	0.30
ε	0.10	0.10	0.10	0.10	0.10
total(rms)	0.26	0.18	0.20	0.27	0.37

* Note: This accountsfor uncertainties in composition due to impurities (mainly C and H) present in the uranium.

c) Experimental results :

The experimental results for the five media after all corrections are compared in table IX.

TABLE IX : K-VALUES OF EXPERIMENTAL TEST REGIONS

	UK1	SNEAK 8	SNEAK 8Z	ZEBRA 8H	UK5
$\frac{\delta k_{cell}}{\delta k_5}$	-0.0070 ± 0.0056	0.0140 ± 0.0031	0.0404 ± 0.0034	0.0661 ± 0.0036	0.1385 ± 0.0040
K^+	0.9970 ± 0.0026	1.0065 ± .0018	1.0185 ± .0020	-	1.0645 ± 0.0037
K_∞	0.9970 ± 0.0026	1.0065 ± 0.0018	1.0185 ± 0.0020	1.0300 ± 0.0027	1.0645 ± 0.0037

4.4.2. Determination of k^+ using buckling measurements:

In the case of the exponential experiment UK5-HARMONIE, k^+ is defined by the relation (4-7)

The experimental value for the buckling was :

$$B_m^2 = (10.0 \pm 0.1)m^{-2}$$

The migration area M^{+2} was calculated from its analytic expression :

$$M^{+2} = 0.0063 \text{ m}^2$$

The accuracy on the M^{+2} value was assumed to be ± 5 % . We obtain thus :

$$k^+ = 1.0630 \pm 0.0035$$

5. MEASUREMENT OF REACTION RATE RATIOS:

5.1. " Cell average " reaction rates :

Reaction rate measurements were made in the central cell of the test region, using activation foils or fission chambers. The "cell average" reaction rate of atom type i adopted is:

$$\bar{R}_i = \sum_j \left(r_{ij} \times N_{ij} \right) \Big/ \sum_j N_{ij}$$

where r_{ij} is the average reaction rate of atom type i in plate j, N_{ij} is the number of atoms of type i in plate j

5.2. Capture ratio measurements : σ_{c8}/σ_{f5}

Two techniques have been used: the "absolute" technique and the "thermal comparison" technique

5.2.1. "Absolute " technique :The capture rate is determined by the irradiation of thin U 238 deposits (ZEBRA) or foils (SNEAK) and subsequently counting the Np 239 activity using a Na-I coincidence (ZEBRA) or Ge-Li (SNEAK) spectrometer.
The spectrometer efficiency is determined by using a calibrated Am 243 source deposit [9].

The U 235 fission rate is measured using a fission chamber, standardised by alpha counting and introduced in a reference position . Foil measurements are used to relate the fission rate at this position to the average in the cell.

5.2.2. "Thermal comparison" technique: The measurements in the test region are related to those in a thermal column.

-In ZEBRA the U 238 capture rates are measured by γ-X ray coincidence counting of Np 239 activity induced in metallic foils of natural (test zone) or depleted (thermal column) uranium using a Na-I spectrometer with a detection window set at 95 -117 keV. U 235 fission rates are measured by integral counting of the fission product activity above 1,28 MeV induced in foils and by using fission chambers.

-In ERMINE the U238 capture rates are determined by counting at 74 KeV of the U239 activity induced in metallic foils of 0.04 % depleted uranium, using a Ge-Li spectrometer. In order to correct this result for the γ-activity of fission products, the γ-activity in a window at 58-66 KeV is measured : it is assumed that the ratio between U 238 and U 235 is the same at 74 KeV and in the window. The U 235 fission rate is determined using fission chambers [87].

-In HARMONIE the capture rates are measured by counting of the Np239activity induced in metallic foils of 0,41%-depleted uranium, with a detection window set at 75-135 KeV. The results are corrected, in order to take into account the γ- activity of the fission products: it is assumed that the ratio between U 235 and U 238 is identical in the window, and above 511 KeV . The U 235 fission rates are obtained by counting the γ- activity induced in uranium foils above 511 KeV. A yield correction is applied : it is obtained by comparison with foils and fission chambers [87].

5.3. Fission ratio measurements : $\sigma_{f_8}/\sigma_{f_5}$

The fission ratio $\sigma_{f_8}/\sigma_{f_5}$ is measured with enriched and natural uranium fission chambers, intercalibrated in a thermal column. Foil measurements are used

to obtain the " cell average " reaction rates.

In ZEBRA the solid state track recorder (SSTR) method was been applied . The damage tracks are counted on a Quantimet B television image analyser coupled to an optical microscope[10].

5.4. Heterogeneity measurements :The heterogeneity of the reaction rates in the cell was measured, in ZEBRA and SNEAK, using foils inside or between the different plates. The distributions across the plates were found by foil measurements at different positions.

In ERMINE and HARMONIE the foils were placed between the different rods.

5.5. Spectrum measurements: Measurements of the neutron spectrum at the centre of the test region were made using lithium -6 semiconductor sandwich spectrometers (ZEBRA) and proton recoil counters (SNEAK,ERMINE,HARMONIE

5.6. RESULTS:

The experimental values are first corrected for the perturbations introduced by the foils. Additional corrections are required to produce data for comparison with theoretical predictions for an infinite lattice. Two comparisons are used :

a) fundamental mode (with leakage): a correction factor f is applied for the finite-size effect.
b) static mode (without leakage): in addition to the f factor , a second correction factor is applied, in order to correct the spectral indices to the static mode . This factor is of the form

$$1 + g \times (k_\infty - 1)$$

The values of f and g, calculated for σ_{f8}/σ_{f5} and σ_{c8}/σ_{f5} in the different assemblies and given in table X, show a small dependence on the nuclear data ($\leqslant 0,3$ %).

TABLE X : CORRECTION FACTORS FOR REACTION RATE RATIOS

ASSEMBLY		ERMINE UK1	SNEAK 8	SNEAK 8Z	ZEBRA 8H	ERMINE UK5	HARMONIE UK5
data set		CAD	KFK	KFK	FGL	CAD	CAD
σ_{f8}/σ_{f5}	f	0.992	0.998	0.998	0.994	0.998	0.970
	g	-	- 1.09	- 1.10	- 1.08	-	-
σ_{c8}/σ_{f5}	f	1.007	1.002	1.001	1.004	1.004	1.005
	g	-	+0.09	+ 0.11	+ 0.10	-	-

The experimental " cell average " values of the spectral indices are given in table XI.

TABLE XI : CORRECTED RESULTS OF REACTION RATE RATIO MEASUREMENTS

Mode	Spectral index	ERMINE UK1	SNEAK 8	SNEAK 8Z	ZEBRA 8H	ERMINE UK5	HARMONIE UK5
Fundamental ($B^2 \neq 0$)	$\frac{\sigma_{f8}}{\sigma_{f5}}$ (1)	$.0220 \pm .00022$	$.0224 \pm .0006$ *	$.0227 \pm .0006$	$.0233 \pm .0006$	$.0243 \pm .00025$	$.0244 \pm .00025$
	$\frac{\sigma_{f8}}{\sigma_{f5}}$ (2)		$.0226 \pm .0005$ *		$.0240 \pm .0008$		
	$\frac{\sigma_{c8}}{\sigma_{f5}}$ (3)		$.115 \pm .003$		$.115 \pm .003$		
	$\frac{\sigma_{c8}}{\sigma_{f5}}$ (4)	$.117 \pm .0015$	$.118 \pm .0015$ *		$.112 \pm .002$	$.116 \pm .0015$	$.119 \pm .0015$
Static ($B^2 = 0$)	$\frac{\sigma_{f8}}{\sigma_{f5}}$ (1)		$.0222 \pm .0006$	$.0222 \pm .0006$	$.0225 \pm .0005$		
	$\frac{\sigma_{f8}}{\sigma_{f5}}$ (2)				$.0232 \pm .0008$		
	$\frac{\sigma_{c8}}{\sigma_{f5}}$ (3)		$.115 \pm .003$		$.1155 \pm .0025$		
	$\frac{\sigma_{c8}}{\sigma_{f5}}$ (4)				$.1125 \pm .0020$		

(1) Foils and chambers.
(2) SSTRS
(3) Absolute method
(4) Thermal comparison
* Measurements performed in SNEAK by the Cadarache group.

6. EXTRAPOLATION TO THE CASE OF MINIMUM ENRICHMENT :

The enrichment defined as : (atoms U235/atoms U235 + atoms U238) and the reaction rate ratios, for a pure uranium lattice with k-infinity exactly equal to unity, were obtained by extrapolation of the experimental results from the five cores. In order to eliminate systematic errors, three extrapolation methods were employed.

6.1. $\langle C/E \rangle$ Method : This is the most direct method. All the experimental results are used, in order to obtain, for each parameter, the mean value $\langle C/E \rangle$ of the ratio of calculation and experiment. The five assemblies are close to homogeneous ($\leqslant$ 0,2 % in k-infinity) and the contributions from structure are relatively small ($\leqslant$ 1,8 % in k-infinity). We can therefore apply the mean values of $\langle C/E \rangle$ to the " $k_\infty = 1$ " homogeneous calculations without structure, and thus obtain the expérimental minimum enrichment and reaction rate ratios.

Table XII gives the comparisons C/E with the FGL 5 calculations, and the mean values $\langle C/E \rangle$ used for each parameter.

6.2. .Regression method: The experimental results are reduced by calculations to the case of homogeneous composition with an average density and an average mass of structural material - The corrections are very small ($\leqslant$ 0,3 %) 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. The values are corrected by calculations in order to obtain the parameters for the pure uranium medium with $k_\infty = 1$ (i,e, without structure) In this method no assumption is made on the varation of the parameters versus enrichment.

TABLE XII : SUMMARY OF C/E VALUES (FGL 5)

Assembly	C/E for k^+ or k_∞	C/E for σ_{c8}/σ_{f5}	C/E for σ_{f8}/σ_{f5}
ERMINE UK1	1.003	1.010	1.038
SNEAK 8	0,996	1.029	1.035
SNEAK 8Z	0,998		1.038
ZEBRA 8H	0,995	1.038	1.022
ERMINE UK5	0,997	1.005	1.041
HARMONIE UK5	0,998	0,980	1.037
$\langle C/E \rangle$	0.998 ± 0.0015	$1.015 \pm .015$	$1.032 \pm .008$

The results of the least square adjustment are given on Figure 1 . The calculated values with the Cadarache cross section set are also shown on the figure

Remark: In view of the dispersion of the experimental results, it is not possible to use the regression method for the capture measurements.

6. 3. ρ_8/ρ_5 method : It was found by calculation that the ratio ρ_8/ρ_5 of the reactivity worth per gram of U238 to the worth of U235 is insensitive to small changes in enrichment and stainless steel content and to the spectrum mismatch. Using directly the reactivity measurements of the core materials, we obtain the critical enrichment from the data of each assembly.

We have thus :

$$\frac{\delta k_U}{\delta k_5} = 1 + \frac{m_8}{m_5} \times \frac{\rho_8}{\rho_5}$$

and

$$\frac{\rho_8}{\rho_5} = \frac{m_5}{m_8}\left[\frac{\delta k_U}{\delta k_5} - 1\right] \qquad (6-1)$$

where δk_U is the reactivity worth of the uranium in the cell and m_5, m_8 the ^{235}U and ^{238}Uranium masses in the cell. For the homogeneous medium with $k_\infty = 1$, we have

$$1 + \left(\frac{m_8}{m_5}\right)_{k_\infty=1} \times \frac{\rho_8}{\rho_5} \simeq 0$$

or

$$1 + \left(\frac{1-E}{E}\right) \frac{A_8}{A_5} \frac{\rho_8}{\rho_5} = 0 \qquad (6-2)$$

where E is the enrichment for $k_\infty = 1$, A_8 and A_5 the atomic mass numbers of U238 and U235.

Using the equation (6-1) and (6-2) we obtained the minimum enrichment E.
In this method, the reactivity measurements of the plates or rods are used directly. The Uranium worth (δk_u) is obtained from these measurements with small corrections for Nickel coating, impurities and heterogeneity.The results, using the KFK data set for the corrections, are given in table XIII.

TABLE XIII: MINIMUM ENRICHMENT FROM P_8/P_5 METHOD.

Assembly	ERMINE UK1	SNEAK 8	SNEAK 8Z	ZEBRA 8H	ERMINE UK5
$\frac{P_8}{P_5}$	-0.0589 ± 0.0005	-0.0579 ± 0.0003	-0.0581 ± 0.0004	-0.0577 ± 0.0005	-0.0578 ± 0.0005
E (%)	5.63 ± 0.05	5.54 ± 0.03	5.56 ± 0.04	5.52 ± 0.05	5,53 ± 0.05

This method provides the experimental minimum enrichment only.

6. 4. Results -

The experimental results for the pure uranium homogeneous lattice with $k_\infty = 1$, using the above three methods, are shown in table XIV.

TABLE XIV: PARAMETERS OF UNIT K_∞ MEDIUM FROM DIFFERENT EXTRAPOLATIONS

Method	$\langle C/E \rangle$	REGRESSION	ρ_8/ρ_5
Cross-section set	F G L	C A D	K F K
$E_{(a/o)}$	5.56 ± 0.02	5.56 ± 0.02	5.55 ± 0.02
σ_{f8}/σ_{f5}	0.02266 ± 0.00020	0.02275 ± 0.00020	
σ_{c8}/σ_{f5}	0.1154 ± 0.0017		

The influence of the extrapolation method was tested using the CADARACHE cross-section set. The results are compared in table XV.

TABLE XV : INFLUENCE OF EXTRAPOLATION METHOD

Cross section set	C A D		
Method	$\langle C/E \rangle$	REGRESSION	ρ_8/ρ_5
$E_{(a/o)}$	5.56 ± 0.02	5.56 ± 0.02	5.54 ± 0.02
σ_{f8}/σ_{f5}	0.02270 ± 0.00020	0.02275 ± 0.00020	

Remark: σ_{c8}/σ_{f5} is only determined by $\langle C/E \rangle$ method.

The influence of the cross section set is shown in table XVI using the $\langle C/E \rangle$ method.

TABLE XVI : INFLUENCE OF CROSS SECTION SET.

Method	$\langle C/E \rangle$		
Cross section set	F G L	C A D	K F K
$E_{(a/o)}$	5.56 ± 0.02	5.56 ± 0.02	5.56 ± 0.02
σ_{f8}/σ_{f5}	0.02266±0.0002	0.02270±0.0002	0.02265±0.0002
σ_{c8}/σ_{f5}	0.1154 ±0.0017	0.1154±0.0017	0.1154 ±0.0017

7. STANDARD CORE : " SCHERZO 556 " .

7.1. Characteristics of the standard core :

Table XIV and XV show that the different extrapolation methods are consistent. The influence of the cross section data set (Table XVI) is negligible. We can thus define the standard homogeneous core in pure uranium with k_∞ =1: "SCHERZO 556". Its enrichment and reaction rate ratios, mean values obtained from table XIV. are given in table XVII, with one σ confidence interval.

- TABLE XVII. SCHERZO 556 -

Enrichment (a/o)	5.56 $\pm$ 0.02
k_∞	1.000
σ_{f_8}/σ_{f5}	0.0227 $\pm$ 0.0002
σ_{c_8}/σ_{f5}	0.1154 $\pm$ 0.0017

7.2. Comparison of experimental and calculated parameters.

The calculations, performed for " SCHERZO 556" using the three data sets are compared with the experimental results.

Table XVIII gives the deviations $\frac{\text{Calc-Exp}}{\text{Calc}}$ in %.

TABLE XVIII: "SCHERZO 556 ": COMPARISON OF EXPERIMENT AND CALCULATION.

$\left(\frac{C-E}{C}\right)$ in %	FGL5	CAD	KFK
k_∞ or k^+	- 0.20	- 0.13	- 0.60
σ_{f8}/σ_{f5}	+ 3.0	+ 1.6	+ 0.9
σ_{c8}/σ_{f5}	+ 1.5	+ 1.5	+ 3.4

7.3. Conclusion: This "SCHERZO 556" core, resulting from european "unit k_∞" lattices, is proposed as an international standard for nuclear data tests. There is very good agreement between k_∞ and F8/F5 measurements using different experimental techniques and different methods of analysis. However, the present dispersion of C8/F5 measurements indicates the possibility of unidentified errors; nevertheless the present accuracy on the final average value obtained from independant experimental techniques is encouraging but can certainly be improved. It is hoped that these studies will lead other countries to test their experimental data against this simple and attractive standard.

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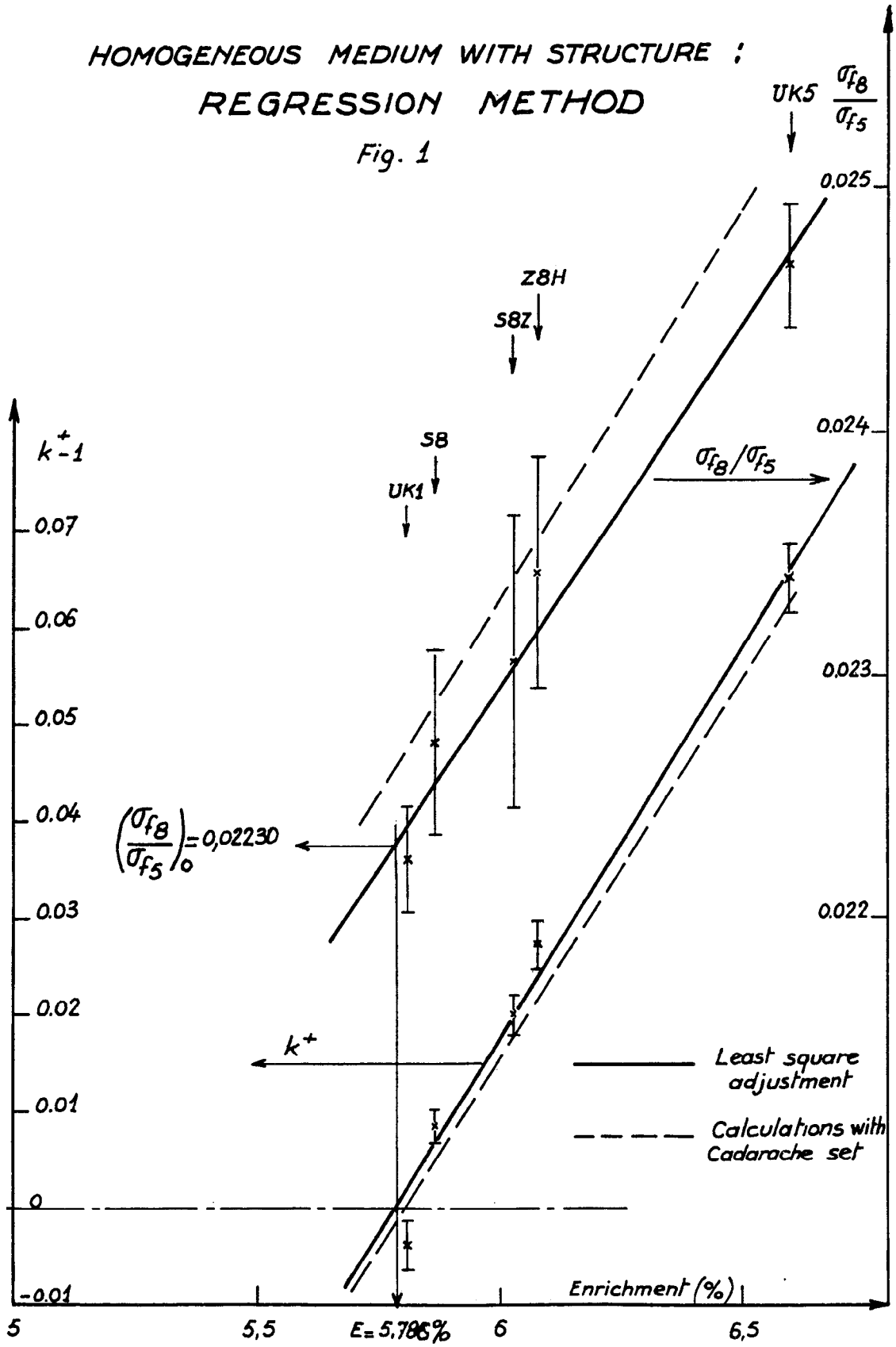
HOMOGENEOUS MEDIUM WITH STRUCTURE :
REGRESSION METHOD
Fig. 1
UK5
Z8H
S8Z
S8
UK1
$k^+ - 1$
σ_{f8}/σ_{f5}
$\left(\frac{\sigma_{f8}}{\sigma_{f5}}\right)_0 = 0{,}02230$
k^+
Least square adjustment
Calculations with Cadarache set
Enrichment (%)
E = 5,786 %
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0.025
0.024
0.023
0.022
5
5,5
6
6,5

Discussion

F. HELM : Could Dr. Fischer or Dr. Iijima comment on the fact that the calculated values for K_∞ are so much better in agreement with experiment in the European paper than in the Japanese one?

T. IIJIMA : I am also surprised at the marvellous agreement of your calculations with experiments. Our calculations were made using rather old and unadjusted data sets. FGL-4 is an adjusted data set. Are the CAD and the KFK adjusted by using these integral data? I should like to point out that adjustment made using such unit K-infinity data may lead to inappropriate change in cross sections unless the neutron spectrum is properly calculated.

J. BUSSAC : This is only a personal comment. I wish to point out the importance of the common French-Germany-UK paper presented by Dr. Fischer. First, it illustrates the high interest of international collaboration to improve the accuracy and the confidence in some fundamental data. And secondly, I am convinced that a well known standard, properly chosen like SCHERZO 556 will, no doubt, be very useful in future for fast reactor physics.

E. FISCHER : A first version of the KFKINR set was tested against a series of critical assemblies. Though the results for most cores were satisfactory, K_∞ of ZEBRA-8H was rather strongly underpredicted. After a change in σ_{in} of U238, this parameter was also calculated fairly well. In this sense, the final version of KFKINR is adjusted to ZEBRA-8H. According to Mr. Barré and Mr. Rowlands, these results were used in the adjustment to produce the Cadarache III and FGL-5 set.