PREMIER MINISTRE
COMMISSARIAT A
L'ÉNERGIE ATOMIQUE

PHYSICS EXPERIMENTS IN GRAPHITE LATTICES

by

P. BACHER and F. COGNE

Report C.E.A. n° 2157

1962

CENTRE D'ETUDES
NUCLÉAIRES DE SACLAY

CEA 2157 - BACHER P., COGNE F.

EXPERIENCES SUR LES RESEAUX A GRAPHITE (1962)

Sommaire - On décrit les différentes méthodes expérimentales utilisées pour déterminer les paramètres physiques de réseaux à uranium-graphite. Il s'agit d'expériences globales : mesures absolues et relatives de laplaciens, mesures de sections efficaces effectives par activation et par analyses de combustibles irradiés, mesures de structures fines.

Un certain nombre de résultats expérimentaux sont communiqués.

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PHYSICS EXPERIMENTS IN GRAPHITE LATTICES (1962)

Summary - A review is made of the various experimental methods used to determine the physics of graphite, natural uranium lattices : integral lattice experiments ; both absolute and differential, effective cross section measurements, both by activation methods and by analysis of irradiated fuels, fine structure measurements.

A number of experimental results are also given.

- Report C.E.A. n° 2157 -

Département des Etudes de Piles

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Symposium on the Physics of Graphite Moderated Reactors

Bournemouth, 4th - 7th april 1962

- 1962 -

PHYSICS EXPERIMENTS IN GRAPHITE LATTICES

Introduction

The French experimental program for the study of the physics of natural uranium, graphite moderated reactors is primarily based on integral measurements, either of lattice properties or of effective cross sections.

The integral lattice properties are determined either by absolute buckling measurements or by progressive replacement experiments in a critical assembly. Both of these methods have given excellent results : as early as 1956, they have been tested in G-1 and led to a prediction of the critical size of G-2 within 1%. The need for an extensive survey of lattice parameters : lattice pitch, channel diameter fuel elements of different geometries, etc ... has led since to the construction of a critical facility (MARIUS) specially designed for the progressive replacement experiments

Additional information are derived during those experiments, for instance on anisotropy, reflector savings, cell fine structure, etc ...

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Correlations based only upon these integral lattice experiments may lead to important errors on the neutron balance. Moreover, information is required on the effect of irradiation and temperature on lattice properties. One approach to both these problems is to determine effective cross sections for U^{28}, Pu^{49}, Pu^{40}, etc.... Several types of experiments are done to this effect :

- Activation measurements of Pu^{49} and U^{25} detectors are done in MARIUS to determine the ratio of effective fissior cross sections in various lattices.

- Analyses of fuels irradiated in the Marcoule reactors at several temperatures yield conversion factors, the ratio of Pu^{49} capture to U^{25} absorption, etc... Those analyses are based on isotopic dilution and mass spectrometry and can be accurate enough to check for instance the temperature dependance of plutonium cross sections.

- Oscillation of plutonium bearing fuel elements. Two quantities are measured simultaneously : a local signal function of the difference of absorption between the sample and a standard, and a general signal, function of the differer ce in η . The oscillation therefore gives effective values for Σ_a and $\nu\Sigma_f$. It is essential for this experiment to be done in spectrum conditions as close as possible to those existing in power reactors. For this reason, this oscillation technique is being developped in MARIUS, where it was first tested last summer with encouraging results.

Further information comes from the commissioning experiments and from the operating experience of the Marcoule reactors. This will be discussed later on in this symposium by A. Teste Du Bailler.

The first part of this paper will deal with integral experiments on lattices - buckling and replacement measurements; the second chapter with some of the additional measurements done in MARIUS, and the third with effective cross section measurements.

I Integral lattice experiments

A - Absolute buckling measurements

The buckling measurements are done by placing detectors or a fission chamber in specific positions of the lattice : either at the boundary of two cells, or, at least for the detectors, on the end caps of fuel elements.

Fission chamber measurements are done one point at a time. Control rods are lifted clear out of the reactor in order to obtain a positive period (100 to 160 seconds e folding time). They are dropped when the integrated counting rate on the fission chamber reaches about 150 000. Another fission chamber is used as monitor to intercalibrate the measurements. The main advantage of the fission chamber measurements is that one knows at once if they are good or bad. However they are lengthy experiments (about 8 days for one radial buckling experiment), and it is generally more convenient to use detectors.

The detectors used are 10 mm diameter Mn foils. Integrated count rates range from 100 000 to 200 000 (about 50 000 c/mn). Five counters are used and each detector goes on all five installations. The statistical counting error is thus of the order of 2.10^{-3}, and the error on detector coefficient is of the same order. Altogether, the accuracy on each flux point (taking into account positionning errors) can be estimated at 5.10^{-3}.

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The main problem in the analysis of radial flux plots arises from the coexistence of two zones : buckling measurements are done in a square central zone, the lattice pitch of the outer zone being different. Therefore one has to deal with spectrum and harmonic effects. Corrections are calculated for both effects, using a two dimensional two group diffusion theory code. The lattice pitch of the outer-zone being 192 mm square, that of the central zone 224 mm square, the corrections however are not very important :

- nought for $r < 110$ cm
- $< 1\%$ for $110 < r < 120$ cm
- $< 8\%$ for $r > 120$ cm (the maximum radius used in the central square is of the order of 150cm)

A least squares analysis is then made to determine the extrapolation radius. In order to detect any systematic error in the correction factors, the analysis is first done with points near the origin, and points of greater abscissa are added one or two at a time. The result is a plot of the extrapolated radius versus the number of points taken into account.

This method will be illustrated on an example. Figure 8 shows the radial flux plots measured in the central zone of MARIUS, with a lattice pitch of 224 mm, a channel 70 mm in diameter, and a solid fuel element 31 mm in diameter. Mn detectors were placed on the end caps of the fuel, in a fourth of the channels. The points corrected by the two dimensional (x-y) calculation are also plotted. The result

of the least squares analysis is shown on figure9. After some variations when only a few central points are included in the analysis, the value of the extrapolated radius is quite stable at Re = 248.2 ± 0,5 cm. The statistical accuracy quoted above is in fact a little too high. Several independant measurements are usually made both with detectors in the moderator and in the fuel, and with fission chambers, and the dispersal of the results gives a fair estimate of the error. In the case under consideration, the weighted average of seven measurements is Re = 248 ± 1 cm.

There are no difficulties for axial flux plots, The accuracy is high and for the same lattice, the weighted average for four measurements is 580 ± 1 cm.

The axial and radial bucklings for the above lattice give a good idea of the total accuracy :

$$B^2_{\perp} = .939 \pm 0.009 \ m^{-2}$$

$$B^2_{//} = .295 \pm .001 \ m^{-2}$$

B. Progressive Replacement Experiment

This method has already been described in the 1958 Geneva Conference paper P/1191 (4). Its application to MARIUS however is somewhat different from what it was during the commissioning experiments of the Marcoule reactors.

Fuel elements of a "reference" lattice are progressively replaced by the fuel elements of the lattice to be studied. The number of channels involved is chosen in order to have as high a symetry as possible in the central region, for instance 12, 16, 24, 32, 44 and 52 channels.

A supercritical approach is made at each of those steps, by changing the loading of the reactor at the core-reflector boundary, and making doubling time measurements. Extrapolation to zero-reactivity yields the critical radius, with an accuracy equivalent to 3 to 5.10^{-5} in reactivity. The change in critical radius versus the number of fuel channels replaced is plotted in figure 10 for several experiments in the same reference lattice.

This change is due to two separate effects: a volume term due to the difference in what can be called the fondamental properties of the two lattices (B^2 or k_∞) , and a boundary term due to the difference in the spectra of the two lattices. The relative importance of the latter decreases when the size of the central region increases, which allows for a separation of the two effects.

The analysis of this experiment is complex, and can be best explained by using a simple one group perturbation theory. It is then convenient to speak in terms of reactivity rather than critical size. Starting from the diffusion equation :

$$D \nabla^2 \Phi + \left[(k-1)\Sigma_a - D\frac{\pi^2}{H^2}\right]\Phi = 0$$

a change in the properties of the lattice in a central region of volume V_1 can be related to a change in reactivity :

$$\rho = \Delta\left[(k-1)\Sigma_a - D\frac{\pi^2}{H^2}\right]\frac{\int_{V_1}\varphi^2 dV}{\int_V \Sigma_a \varphi^2 dV} + \Delta D\frac{\int_{V_1}(\text{grad}\,\varphi)^2 dV}{\int_V \Sigma_a \varphi^2 dV}$$

As long as the central region is small, grad $\phi \ll \varphi$ and the last term aan be neglected. The change in axial leakage between the two lattices is also usually very small, and we have approximately :

$$\rho \# \Delta\left[(k-1)\Sigma_a\right]\frac{\int_{V_1}\varphi^2 dV}{\int_V \Sigma_a \varphi^2 dV}$$

$\Delta[(k-1)\Sigma_a]$ appears as the asymptotic value of $\rho\dfrac{\int_V \Sigma_a \varphi^2 dV}{\int_{V_1}\varphi^2 dV}$ for increasing V_1

If one now speaks in terms of changes in critical size, or geometrical buckling(B_g^2), ρ has to be replaced by $K\delta B_g^2$, K being proportional to the migration area of the reference zone.

It can be seen from this very rough analysis that the result of the replacement experiment is not a difference in buckling between the two lattices, but rather a difference in net reaction rates $\left[(k-1)\Sigma a\right]$.

A more detailed analysis is in fact necessary to take into account the boundary effects which do not appear in the one group calculation, and this is done by using two group theory. Moreover, changes in lattices properties are often graat and straight perturbation theory would not give the appropriate weights to the two regions. In order to

overcome this difficulty, an approximate two group calculation of the experiment is made, and a perturbation calculation (6) applied to that. The change in net reaction rates appears as the sum of two terms : one is a first guess and the other a correction derived from the experiment :

$$\Delta[(k-1)\Sigma_a] = \Delta[(k-1)\Sigma_a]_{\text{guessed}} + \delta[(k-1)\Sigma_a]$$

In practice, the correction factor includes errors both on $(k-1)\Sigma_a$ and on the boundary effect, and the latter decreases as $\frac{1}{R}$ when the radius R of the central zone increase Figure II shows the variation of the correction factor (Γ) plotted against 1/R for a given experiment : the lattice pitch is 224 mm; the channel diameter 70 mm, the reference fuel is a 31 mm solid rod and the replacement fuel a 40 mm solid rod. Extrapolation to zero of the best straight line drawn through the points yields :

$$\Gamma_o = \delta[(k-1)\Sigma_a] = (2.1 \pm .1)\,10^{-5}$$

The total error on $\Delta[(k-1)\Sigma a]$ has to include the uncertainty on the migration area of the reference lattice, as can be seen from the one group treatment. Assuming 5% for this uncertainty, and the first guess for $\Delta[(k-1)\Sigma a]$ with standard cell calculations being $4.99.\ 10^{-5}$, the final result is :

$$\Delta[(k-1)\Sigma_a] = (6.09 \pm .35)\,10^{-5}$$

Some experimental results of replacements at the lattices pitches 192 and 224 mm are summarized below. ./...

Some results obtained by the replacement method in MARIUS

1° Pitch of 192 mm

	Absolute measurements $B^2_{\perp}$ (m^{-2})	Absolute measurements $B^2_{//}$ (m^{-2})	Channel diameter (mm)	Fuel geometry diameters (mm)	Σ_a calculated (10^{-3} cm^{-1})	k_∞
Reference lattice	.903	.277	70	28	3.5887	1.08510±.00140
Tested lattices			70	31	4.1870	1.08310±.00140
			70	40× 20.6	5.1226	1.06100±.00140
Reference lattice	.978	.277	70	31	4.1870	1.08270±.00140
Tested lattices			70	28	3.5887	1.08420±.00150
			70	45 x 29	5.4547	1.05130±.00150
Reference lattice	.722	.257	90	28	3.6962	1.08420±.00200
Tested lattices			90	40x20.6	5.3595	1.05140±.00210
			90	45 x 35	4.6466	1.05575±.00300
Reference lattice	.551	.240	110	28	3.8546	1.08610±.00400
Tested lattice			110	40x20.6	5.5543	1.04340±.00400

2° Pitch of 224 mm

	Absolute measurement $B^2_{\perp}$ (m^{-2})	Absolute measurement $B^2_{//}$ (m^{-2})	Channel diameter (mm)	Fuel geometry diameters (mm)	Σ_a Calculated ($10^{-3} cm^{-1}$)	k_∞
Reference lattice	.939	.295	70	31	3.0661	1.09010±.00060
Tested lattices			70	28	2.6542	1.07770±.00100
			70	40	4.1296	1.08430±00060
			70	32.8x10.7	3.1017	1.08720±00075
			70	40 x 20.6	3.6992	1.08620±.00060
			70	45 x 29	3.9187	1.08220±.00070
			70	45 x 35	3.2687	1.07325±.00085
			70	50 x 30	4.8043	1.07145±.00065

The progressive replacement experiment is in essence a differential experiment, and as such its accuracy is very high. It can be further improved by an increased knowledge of the reference lattice, especially of its radial migration area. This can be measured by a critical approach for the reference lattice, but one has to rely then on the delayed neutron contributions. Excellent agreement has in fact been found in MARIUS between the calculated and the experimental M^2 using the Keepin values for delayed neutrons

Moreover, in order to derive the absolute value of $(k - 1)\Sigma a$ for a new lattice, one has to know k_∞ and Σa for the reference lattice. The former is obtained from the buckling measurements and migration areas : $k_\infty \# 1 + M_\perp^2 B_\perp^2 + M_{//}^2 B_{//}^2$. Additional information can be derived from a direct measurement of anisotropy. Σa may be derived from cell fine structure experiments. Those two types of experiments are done in MARIUS and will be briefly discussed in the next chapter. Some interesting results on axial extrapolation length will also be given.

II Additional measurements.

A. Anisotropy

From the above relation between k_∞ , $B_\perp^2$ and $B_{//}^2$, $M_\perp^2$ and $M_{//}^2$, one can see that if $B_\perp^2$ and $B_{//}^2$ are measured for two different core geometries, and the values are plotted in the $(B_\perp^2 , B_{//}^2)$ plane, the slope of the line joining the two points is equal to $(M_{//}^2 / M_\perp^2)$

This experiment can be done in MARIUS, the minimum length of the core being 3m in order to achieve criticality. The results for the reference lattice : 224 mm lattice pitch, 70 mm diameter channel and 31 mm solid rod, are plotted on figure 12. The value for $M_{//}^2 / M_{\perp}^2$ is 1.13 ± .05, a value which seems significantly higher than the value obtained by our present theoretical predictions (7).

B. Cell fine structure

Standard calculations of the average absorption in the cell by the Amouyal - Benoist method (8) are in excellent agreement with monokinetic transport theory S_n or double Pn calculations, to within less than 1% on the ratio of average fluxes in the fuel and the moderator (ϕ u / ϕm). However it may be necessary to take into account spectrum hardening effects in the fuel. Fine structure experiments are done in MARIUS to study this problem.

The measurements are done in the central cell of MARIUS, with Mn detectors, 7 mm in diameter. The positions of the detectors in the fuel are illustrated on figure 13. Subcadmium measurements are also done in the moderator to correct for epithermal effects. The values of the flux are plotted on figure 14 for the usual reference lattice. The experimental flux ratio is :

$$\left(\frac{\phi u}{\phi m}\right)_{\text{corrected}} = .55 \pm .01$$

the value obtained by the Amouyal - Benoist method being .525

C. Axial extrapolation Length

The axial extrapolation length is measured for each reference lattice, and is of particular interest when the channel diameter is changed. The following results have been obtained for the extrapolation length and the reflector saving for the 192 mm lattice pitch and the 28 mm diameter solid rod (core length = 4.80 m, solid reflector thickness =.54m) :

Channel diameter	Extrapolated length	reflector saving
70 mm	5.97 ± .02 (m)	.585 m
90 mm	6.19 ± .025 (m)	. 695 m
110 mm	6.41 ± .04 (m)	. 805 m

The relative variation of the reflector saving is in good agreement with theory.

Measurements of the axial extrapolation length are also done at the end of most replacement experiments, in order to determine whatever correction may be neccessary to account for variations in axial leakage. This correction has in fact always been negligible in normal experiments.

A few replacement experiments have been done however changing the channel diameter by removing a sleeve, but keeping the same fuel. This type of experiment should yield k_∞ , whereas the buckling is measured directly. One could hope to derive M^2. The great variations in axial leakage ($D_{//} \frac{\pi^2}{H^2}$) throughout the experiments call for detailed analysis. A first series of experiments was done for that purpose at the 192 mm lattice pitch, with a 110 mm channel in all the square central zone. Axial extrapolation length was measured in 10 channels across the reactor (figure 15).

III Measurements of effective cross sections

The general purpose of those measurements is to determine a set of effective cross sections for the most important uranium and plutonium isotopes. The ultimate objective is to make reliable predictions of reactivity changes with burn-up. We are primarily concerned, however, with checking various mathematical models derived for the neutron thermalization problem(9). The ratio of plutonium 239 to uranium 235 fission cross section is measured by activation techniques or fission chambers. The conversion ratio, the ratio of plutonium 239 and plutonium 240 capture to uranium 235 absorption are determined by analysis of irradiated fuels.

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Activation measurements

The detectors used for the Pu^{49} and U^{25} fission ratios are 7 mm diameter foils, 3 mm thick, containing respectively1and 2 mg. of Pu^{49} and U^{25} (10). Those detectors can be placed either in the moderator or inside fuel elements in identical positions. The fission rates are determined by counting fission product gamma-ray activities in a NaI photo scintillator with a bias set around 475 KeV. Experiments were made to determine appropriate flux level and irradiation time. The resulting values are about 5.10^8 $n/cm^2/s$ and one hour, giving counting rates of about 100 000 c/mn four hours after reactor shutdown. The Pu/U ratio is nearly constant from the third to the fifth hour after shutdown (figure 16) and this value is not very sensitive to a twofold change either in irradiation time or flux level (less than 1% on the ratio).

Calibration of the detectors is done in a thermal column, obtained by removing the fuel elements from the twenty four central cells of MARIUS. The epithermal to thermal flux ratio in the center of the column is less than. 005, so that the Pu/U ratio measured at that position is very nearly thermal.

One finally derives the ratio of effective cross sections in a given lattice to thermal cross sections.

$$\frac{(\sigma_f^{49}/\sigma_f^{25})_{eff.}}{(\sigma_f^{49}/\sigma_f^{25})_{thermal}} = \frac{(Pu/U)_{cell}}{(Pu/U)_{thermal\ column}}$$

This measurement is done systematically at the end of each replacement experiment in MARIUS. A typical result is that obtained in the moderator of a 224 mm square cell, fuelled with a hollow rod : i. d. = 30 mm. 0.d = 50 mm placed in a channel of diameter 70 mm :

$$(Pu/U)\ \text{cell} = 0.99 \pm 0.01$$
$$(Pu/U)\ \text{thermal column} = .82 \pm 01$$

$$\frac{(\sigma_f^{49}/\sigma_f^{25})_{eff}}{(\sigma_f^{49}/\sigma_f^{25})_{thermal}} = 1.21$$

The same ratio measured with fission chambers is 1.20. Theoretical calculations give for this ratio values ranging from 1.19 to 1. 25 according to the model used.

Analysis of irradiated fuels

Three independent measurements have to be made in order to derive the conversion ratio, $(\sigma_c^{49}/\sigma_a^{25})_{effectiv}$ and $(\sigma_c^{40}/\sigma_a^{25})_{effective}$: depletion of U^{25}, isotopic analysis of plutonium, and Pu^{49} / U^{28} content.

The depletion of U^{25} is obtained by a UF_6 mass spectrometer. The accuracy on the ratio $\frac{U^{25}\ \text{depleted}}{U^{25}\ \text{naturel}}$ is 5.10^{-4}.

The isotopic analysis of plutonium is made with a solid source mass spectrometer. The relative accuracy is a

function of the isotopic content : about 1% on the Pu^{40}/Pu^{49} ratio when this ratio is greater than 1%,5 to 10% on the Pu^{41}/Pu^{49} ratio when it is of the order of 10^{-3}. For higher irradiations, the Pu^{42}/Pu^{49} ratio can also be reached with a good accuracy.

The Pu^{49}/U^{28} ratio is obtained by isotopic dilution followed by mass spectrometry. The tracers presently used are uranium enriched in U^{25} to 93% and Plutonium containing 30% of Pu^{40}. One then can write :

$$\frac{Pu^{49*}}{U^{28}} = \frac{Pu^{49*}}{Pu^{40}} \quad \frac{Pu^{40}}{U^{25}} \quad \frac{U^{25}}{U^{28}}$$

Pu^{49*} including both the original plutonium and the one added with the Pu^{40} tracer. The solid source mass spectrometer measurements of U^{25}/U^{28} and Pu^{49*}/Pu^{40} are accurate to about 1%, but the final accuracy on the Pu^{49}/U^{28} ratio is only about 4%. This accuracy will be improved later to 1,5% when tracers containing 90% Pu become available. Another way of improving the accuracy consists in the use of a Pu^{42} tracer.

In order to derive the desired quantities : $Co = \frac{\sigma^{28}\ eff}{\sigma_a{}^{25}\ eff}$, $\frac{\sigma_c{}^{49}\ eff}{\sigma_a{}^{25}\ eff}$, $\frac{\sigma_a{}^{40}\ eff}{\sigma_a{}^{25}\ eff}$ from the above measurements, corrections have to be made taking into account the destruction of Pu^{49}, Pu^{40}, etc ... by fission or capture of neutrons.

For instance, Co is obtained from Pu^{49} / U^{28} by the following equation :

$$Co = \frac{\sigma^{28}_{eff}}{\sigma^{25}_{a\,eff}} = \frac{P_u^{49}}{U^{28}} \cdot \frac{1}{x}\left[1 + \left(\frac{\sigma^{49}_{a\,eff}}{\sigma^{25}_{a\,eff}} - 1\right)\frac{x}{2!} + \ldots\right]$$

where $x = 1 - \frac{U^{25}}{U^{25}}$ depleted / natural . Similar equations can be written for $(\sigma_c^{49} / \sigma_a^{25})_{eff}$, $(\sigma^{40} / \sigma_a^{25})_{eff}$, etc.. Some of the quantities necessary to calculate the correction factors can be derived from the set of experiments themselves (x for instance), so that the only theoretical values introduced in the correction factors are $(\sigma_c^{49} / \sigma_a^{49})_{eff}$ and $(\sigma_a^{41} / \sigma_a^{25})_{eff}$.

A typical set of values are the following

$$\frac{U^{25}\ \text{depleted}}{U^{25}\ \text{natural}} = .9283 \pm .0005$$

$$\frac{Pu^{49}}{U^{28}} = (.389 \pm .016)\ 10^{-3}$$

$$\frac{Pu^{41}}{Pu^{40}} = .039 \pm .004$$

Assuming for the corrections

$$\sigma_c^{49} / \sigma_a^{49} = .348$$

$$\sigma_a^{41} / \sigma_a^{25} = 2.83$$

N^{28}/N^{25} = 138 in natural uranium, one finds :

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$Co = 79_3 \pm 0.04$	
$\frac{\sigma_c^{49}}{\sigma^{28}_{eff}} = .89_5 \pm .01$	Irradiation temperature 200°C
$\frac{\sigma^{40}}{\sigma^{28}_{eff}} = 1.61_5 \pm .16$	

This type of experiment yields very important information on effective cross sections, and the accuracy will be improved when better tracers become available.

It is already possible with the present results to exhibit the variation of $\sigma_c^{49} / \sigma^{28}_{eff}$ with irradiation temperature, and with improved experimental accuracy a precise check of theoretical prediction will become possible.

Conclusion

The experiments done up to now in MARIUS give us a good knowledge of the properties of cold lattices for the usual pitches of power reactors (190 to 225 mm), and for a wide range of surface to volume ratio of the fuel ($0.9 < \frac{2V}{S} < 2.5$, cross section of the fuel (6 to 20 cm^2), channel diameter (70 to 110 mm). Many other experiments have been done in MARIUS:

- the effect of absorbers, such as molybdenum, has been determined with accuracy, and civilian reactor fuels (EDF1) have been tested; systematic experiments are done on control rods; etc...

The short range program of MARIUS calls for exploratory experiments at very large pitches (320 mm and 288mm), and for the study of plutonium bearing fuel elements, both by replacement methods and oscillation.

The operating experience of power reactors and the analysis of irradiated fuel yield very important information on the influence of temperature on the overall properties of a reactor and on effective cross sections. Accurate knowledge of the physics of the power reactors requires however that experiments be performed in clean conditions and for a wide range of variables. Those studies will be carried out in a hot critical facility, which is planned for the near future at Cadarache. This facility, named CESAR, will operate at temperatures up to 500°C. The experimental techiques will on the whole be the same as those used in MARIUS: absolute buckling measurements, progressive replacements, fuel oscillation.

Acknowledgments

Mr. O. Trétiakoff is responsible for the programme of analysis of irradiated fuels.

MARIUS is operated by Mr. TAICLET and his staff.

M. D'ORVAL and SAUTIEZ have prepared the plutonium and uranium detectors, and the fission chambers.

We have been helped in the analysis of the various MARIUS experiments by members of both EDF and CEA.

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APPENDIX

Description of MARIUS

General layout

MARIUS, built at Marcoule in 1959, became critical on January 6, 1960. It is made up of a cylindrical stack, 6.15m in diameter and 5.88 m long, with horizontal channels. The whole stack is below ground level.

The elementary cells consist of graphite blocks, 192 mm square, with a central channel. Starting from the axis of the stack, there are three separate regions.

- a square central region 2.68 x 2.68 m, made up of 196 elementary cells. This zone serves as reference for the progressive replacement experiments. The lattice pitch and channel diameter can be changed at will by adding graphite planks between the graphite blocks, and changing sleeves in the channels. The various possible pitches range from 192 mm to 320 mm (cf figure 2) and the channel diameters range from 70 to 140 mm.

- a driver region, made up of 336 elementary cells and with a fixed channel diameter (70 mm). The channels can be loaded either with uranium or graphite plugs, so that criticality can be achieved for different loadings of the central region.

- a reflector of outer radius 3.07 m.

Axially, the standard core is 4.80 m long with two symmetrical reflectors .54 m thick. The length of the core can of course be changed for specific experiments, such as anisotropy or reflector saving measurements.

The reactor is controlled with 6 vertical control rods just outside the central region. Figure 3 shows the upper shielding and the control rods.

The main characteristics of MARIUS are summarized in figure 1.

II Experimental facilities

MARIUS was built primarily for progressive replacement experiments. Fuel loading has been made as simple as possible; both ends of the stack can be easily reached by means of platforms, each of which can carry one ton (figure 4). Two ion chambers placed in the reflector are connected to periodmeters, and the total number of readings of doubling time is 24. Reactivity measurements can thus be made to 1 or 2.10^{-6}.

Small experimental channels are provided at the boundary of cells for the absolute buckling measurements. The flux can be measured in any cell of the central zone (figure 5) There is also a vertical channel in the central plane, mainly for fission chamber measurements.

The four central cells can be taken out, including the graphite (figure6). This facility is used mainly for fine structure experiments. A block of graphite, 140 mm square, can be removed independently at the junction of those four cells, and accurate measurements of graphite cross sections by the "danger" method are possible on blocks of graphite weighing about 30 kg.

Oscillator experiments are also done in the square central hole. Figures 3 and 7 show details of the oscillator. Complete trains, one and a half time the length of the core, can be oscillated.

Shielding and electronics have been provided so that the maximum flux possible is of the order of 10^9 n/cm^2/s. Accurate measurements of Pu/U fission ratios, or conversion factors, can thus be made.

Manuscript received 10th of may 1962

MAIN CHARACTERISTICS OF MARIUS

Length of the stack	5.88 m
" of the core	variable
Diameter of the stack	6.14 m
" of the core	variable
Control rods number	6
Maximum number of channels	532
Maximum flux	10^9 n/cm^2/sec

Three regions:

- Central region:	
Pitch	192, 224, 256, 288, or 320 mm
channel	140, 110, 90 or 70 mm in diameter
Number of channels	196 for the 192 mm pitch
fuel	variable (Natural Uranium)
- Outer region	
Pitch	192 mm
Channel	70 Mm
Number of channels	336
fuel	ø 31 Natural Uranium (usually)
- Radial reflector	

Standard experiments:

Absolute buckling measurements
Progressive replacement experiments
Oscillation technique
Fine structure and spectrum measurements
Flux deformation around control rods
Anisotropy. Reflector saving measurements
Diffusion length in graphite

Figure 1

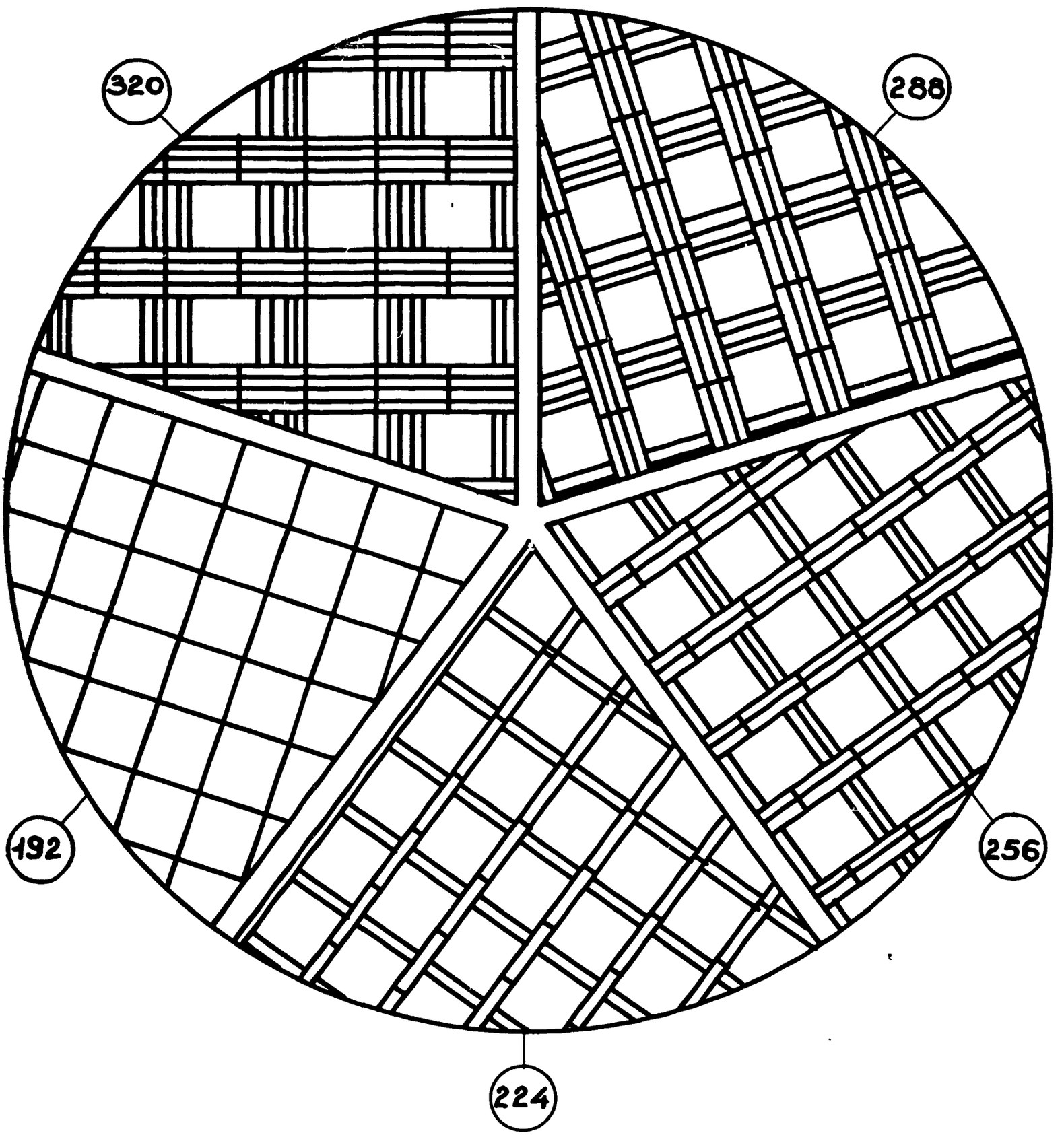

Fig 2 **MARIUS** - Different pitches

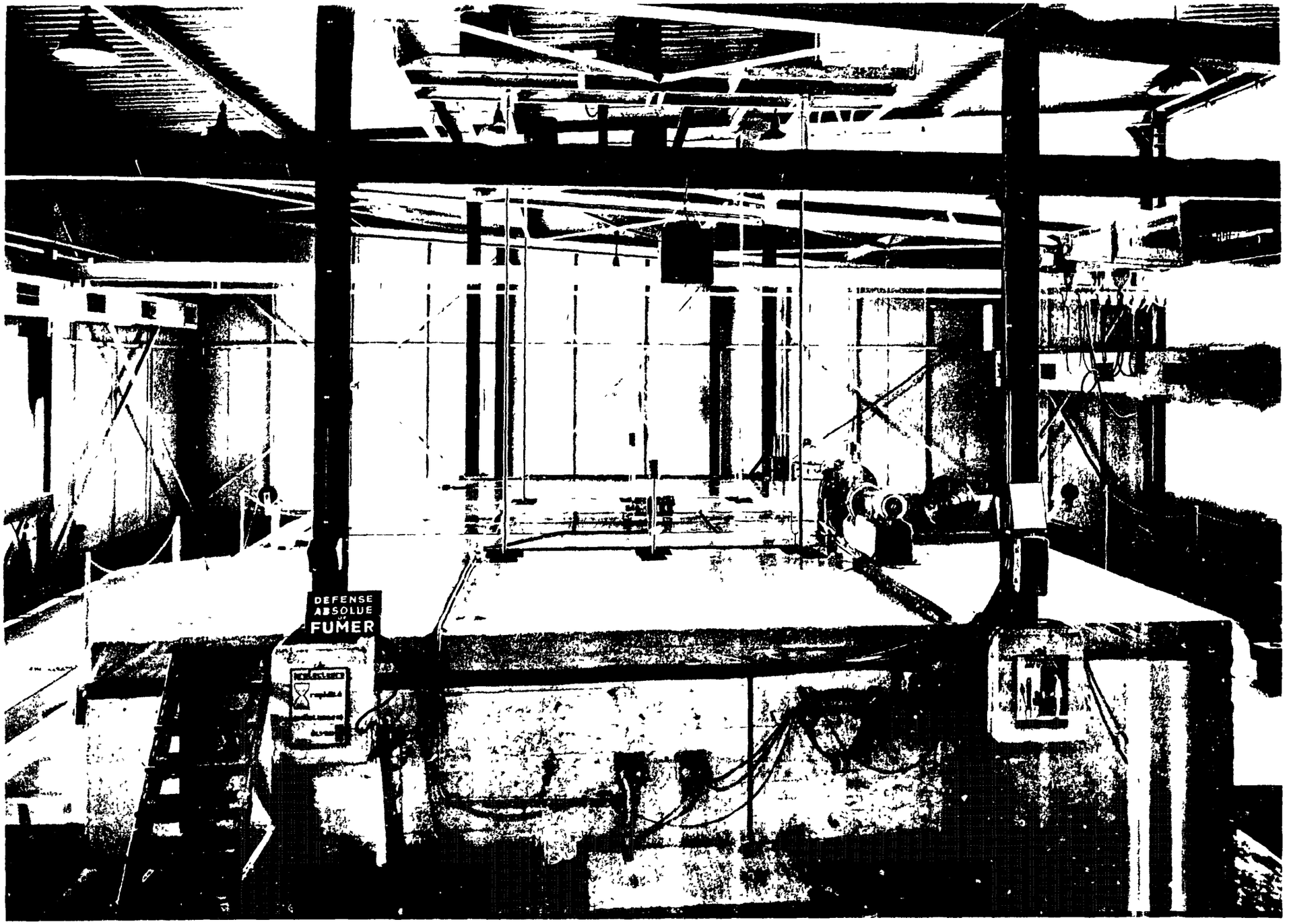

Fig. 3 - Top shield of the reactor - Control rods - Oscillator drive

Fig. 4 - Front view of the reactor

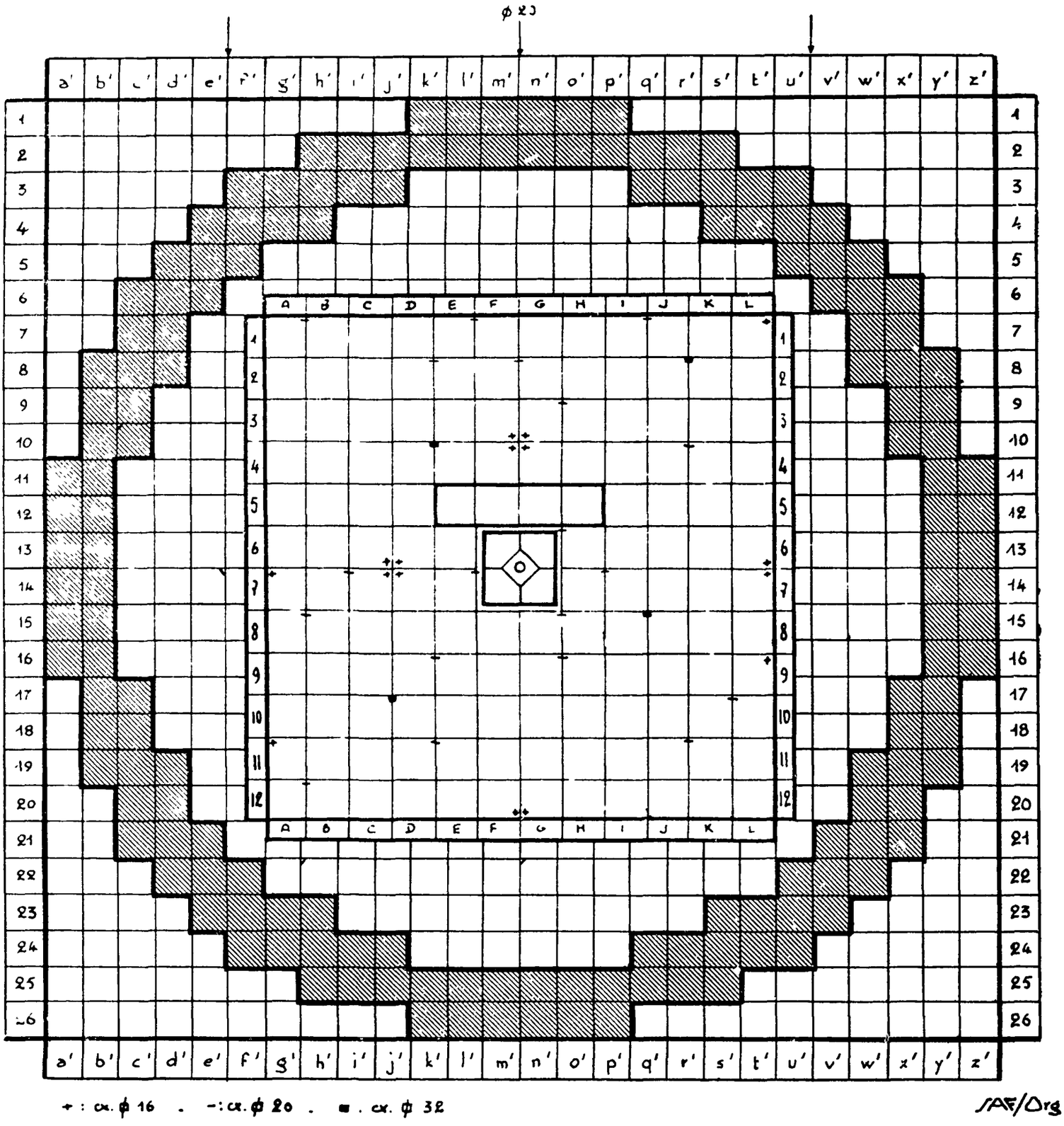

Fig. 5 - MARIUS - 224 mm lattice - flux scanning holes

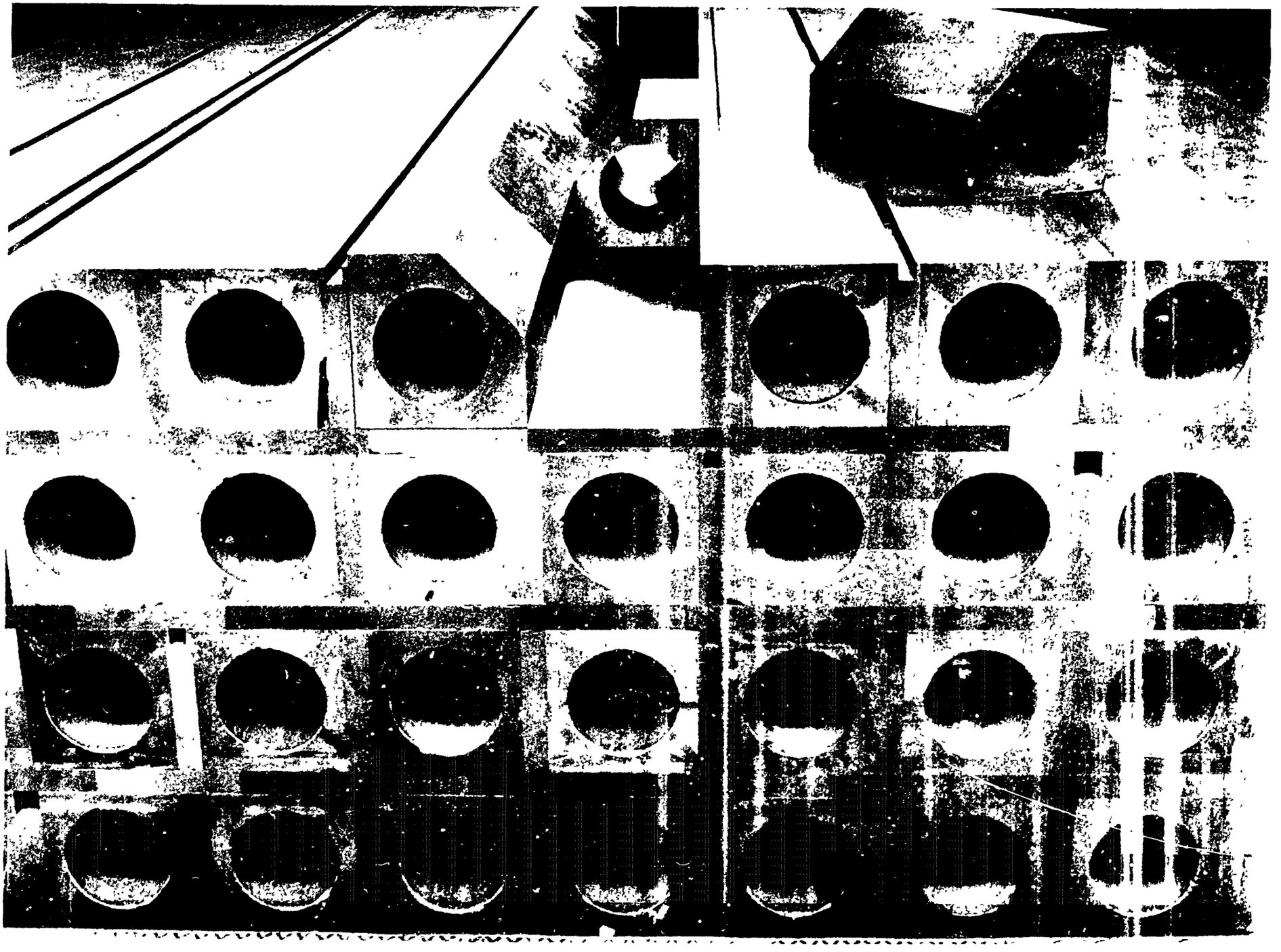

Fig. 6 - Central zone and removable cells during the rebuilding of the stack for the 224 mm pitch

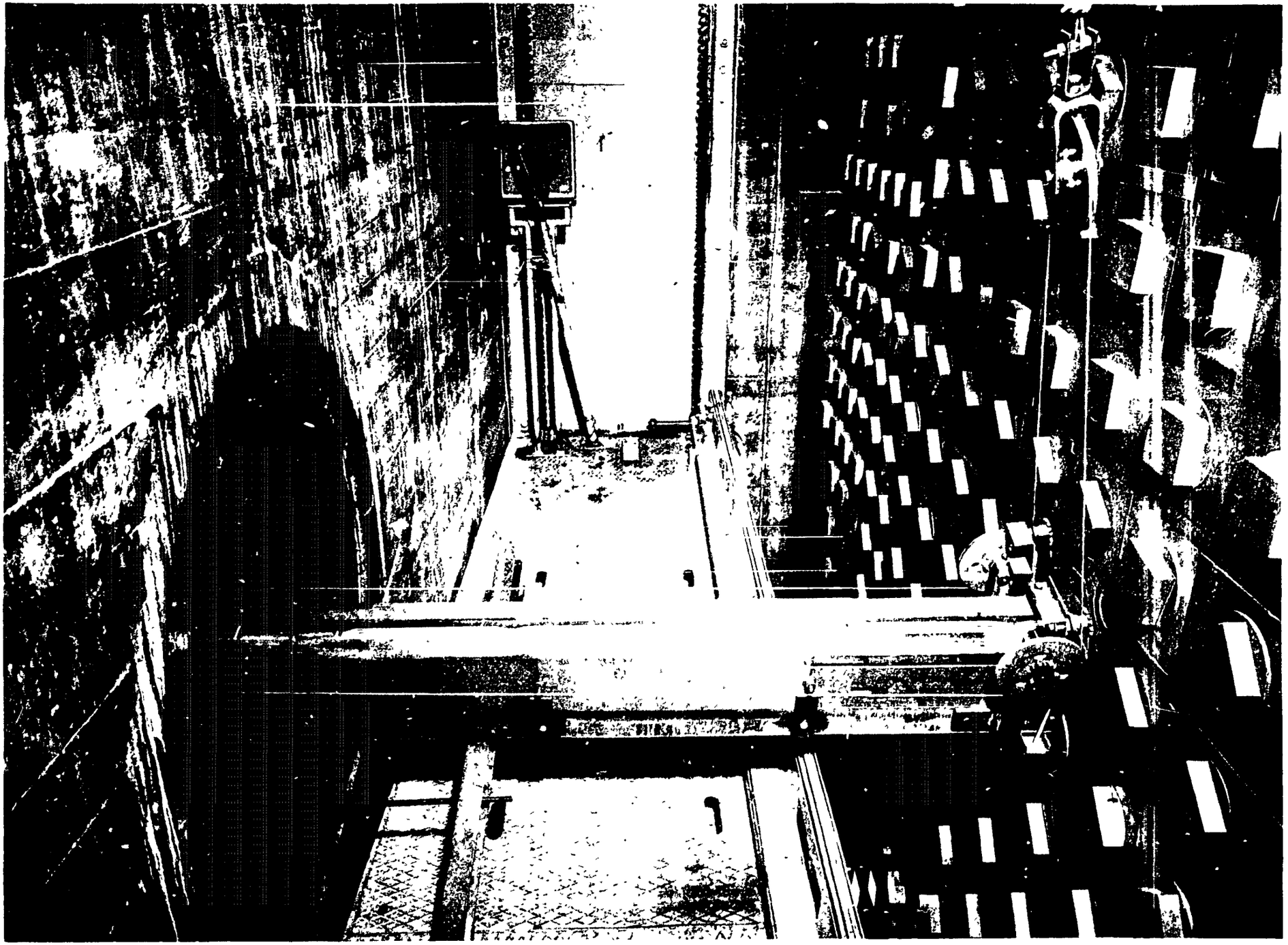

Fig. 7 - Oscillator rig and fuel element train

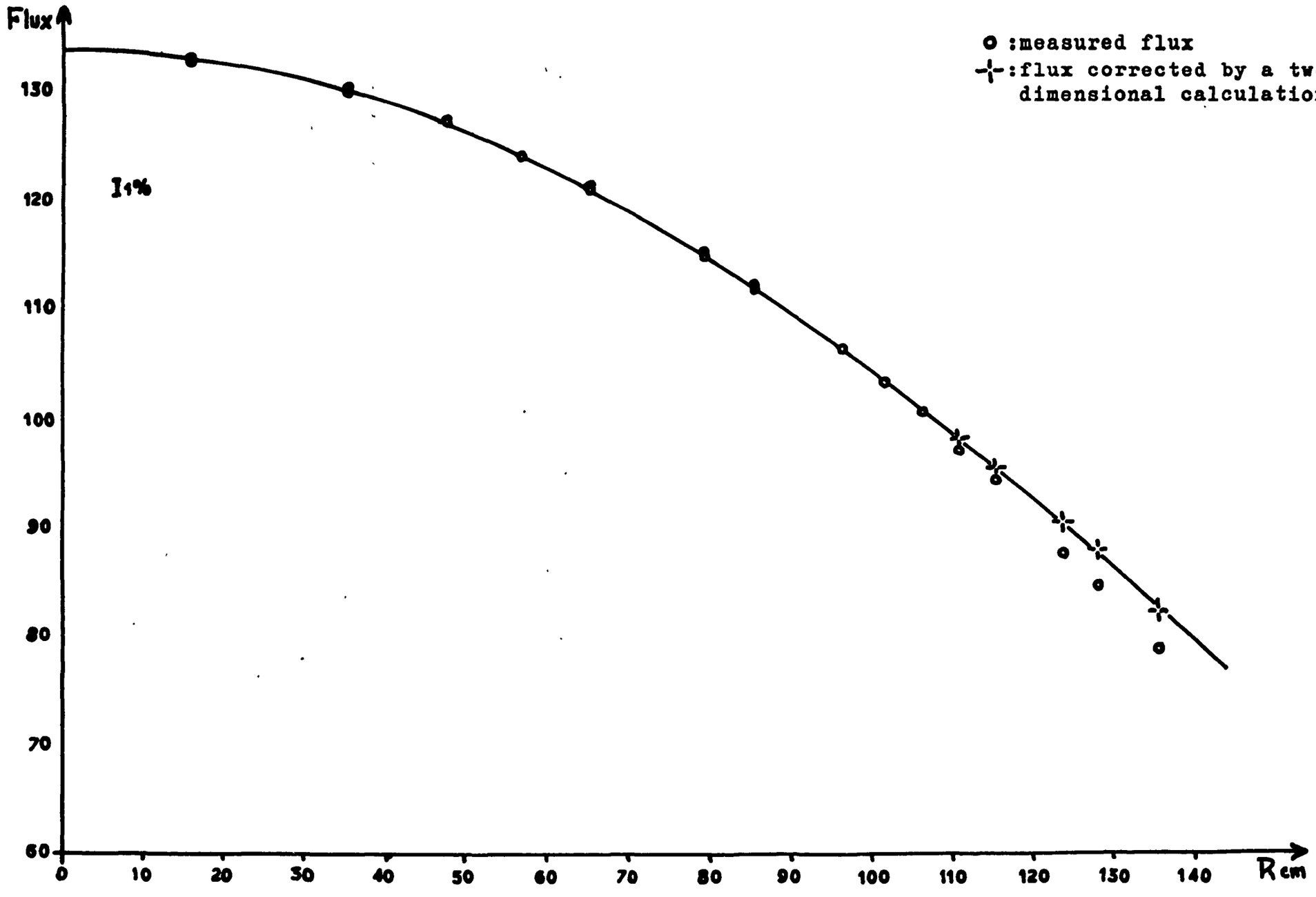

Fig 8 - Absolute buckling measurement in the central square region of MARIUS
pitch : 224 mm
channel diameter: 70 mm
fuel diameter: 31 mm

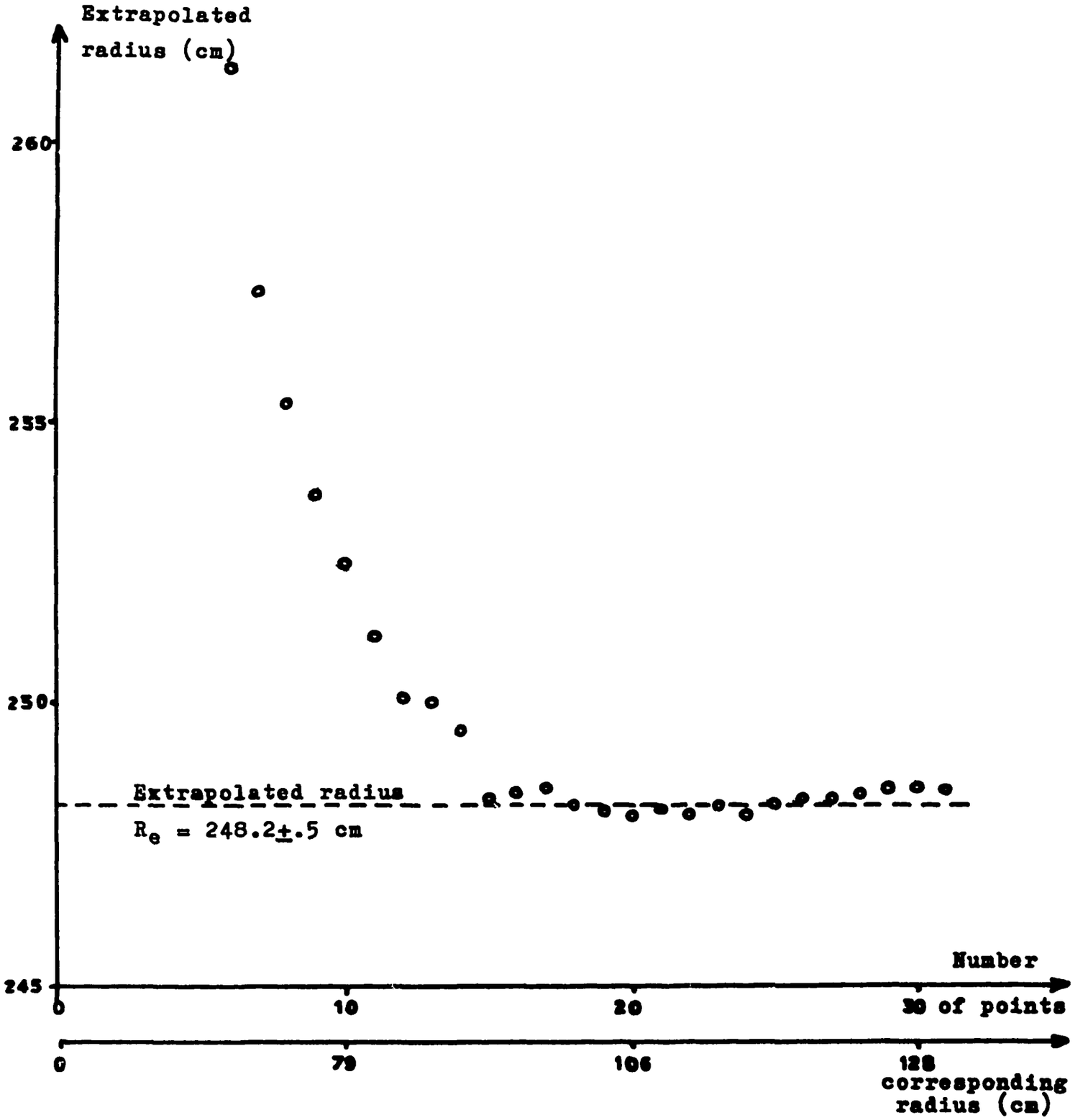

Fig 9 - Absolute buckling measurement - Least squares analysis

Pitch : 224 mm

channel diameter: 70 mm

fuel diameter: 31 mm

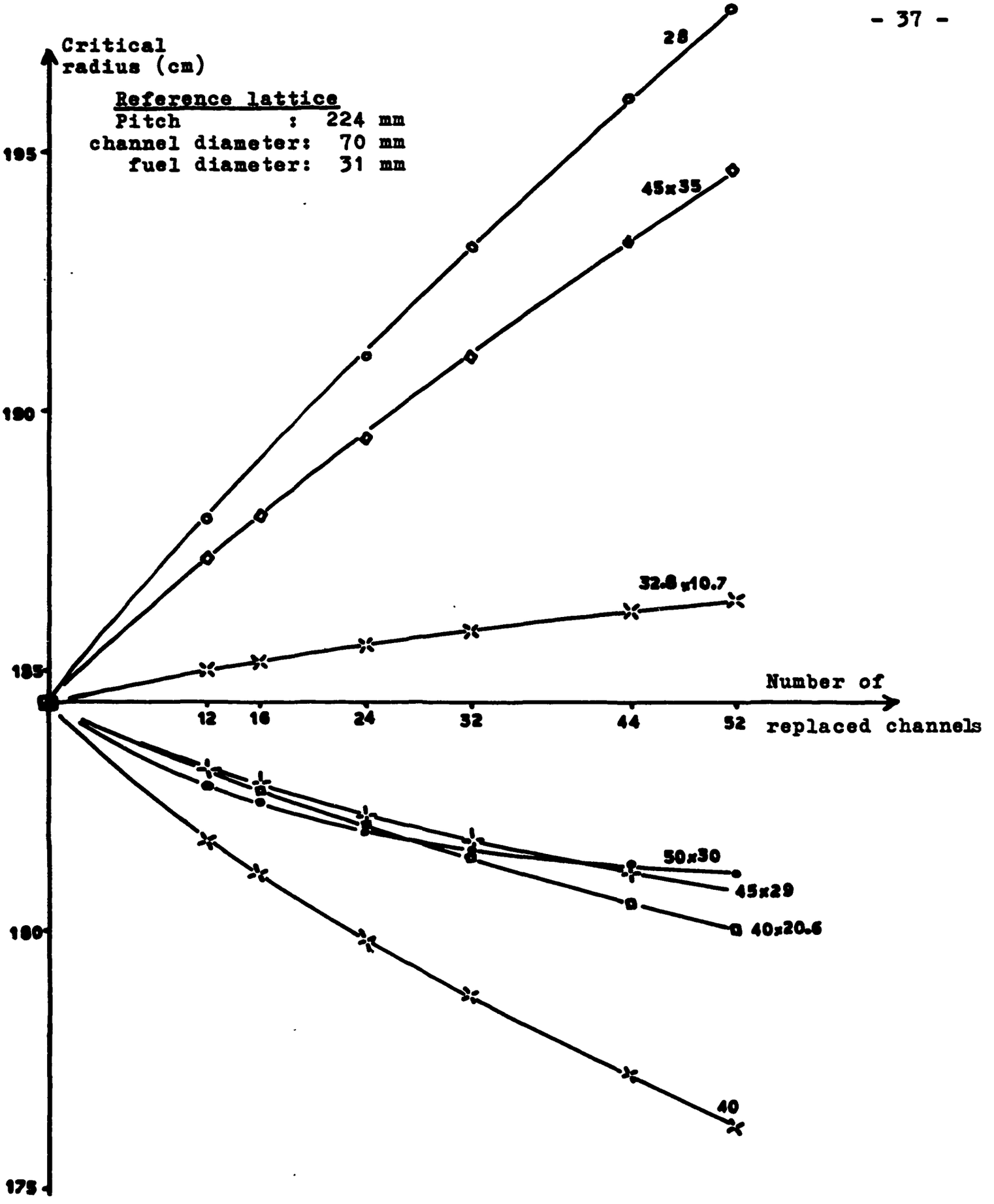

Fig 10 - Progressive replacement experiments - Change in critical radius

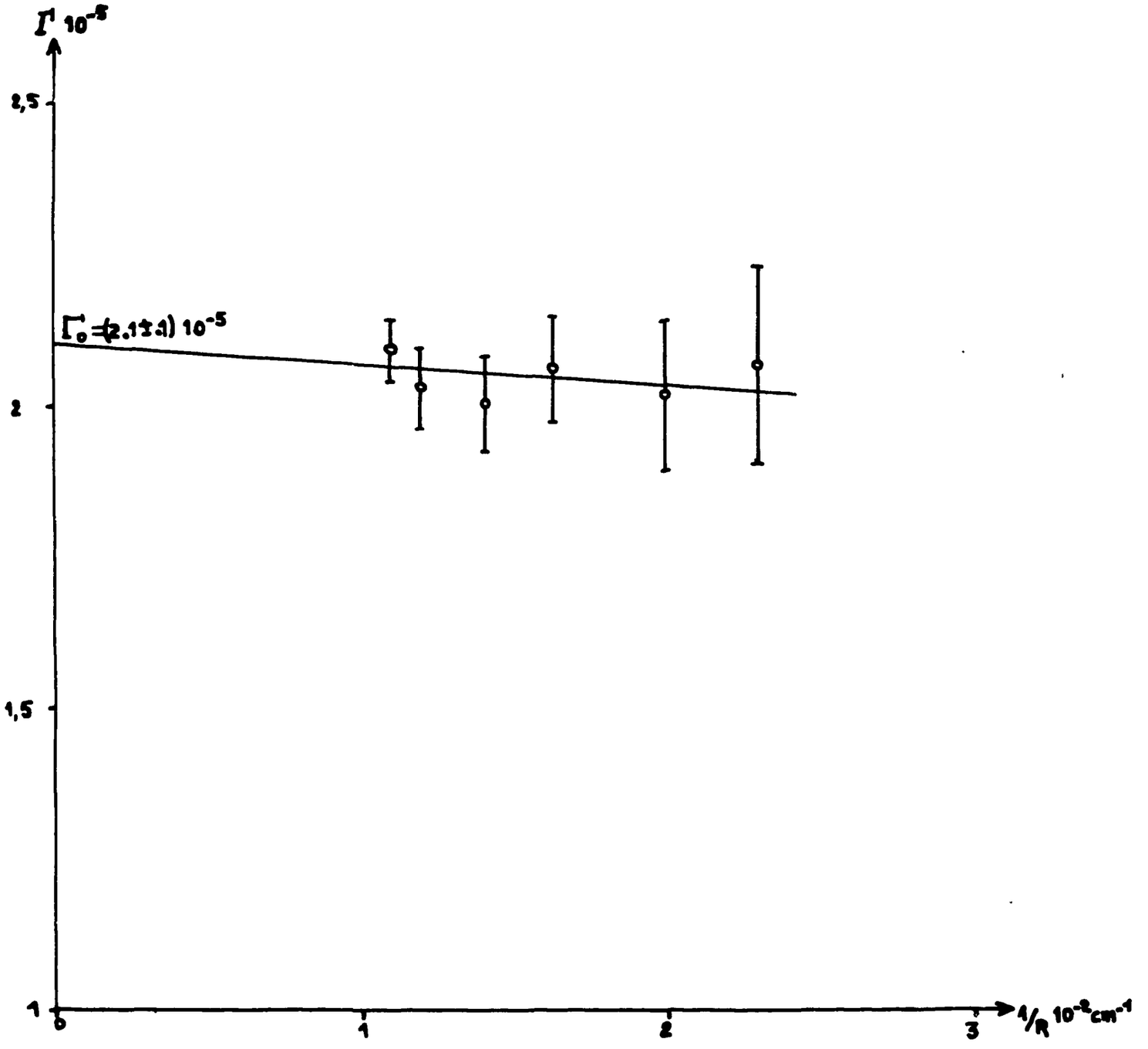

Fig 11 - Progressive replacement experiment - Variation of the correction factor

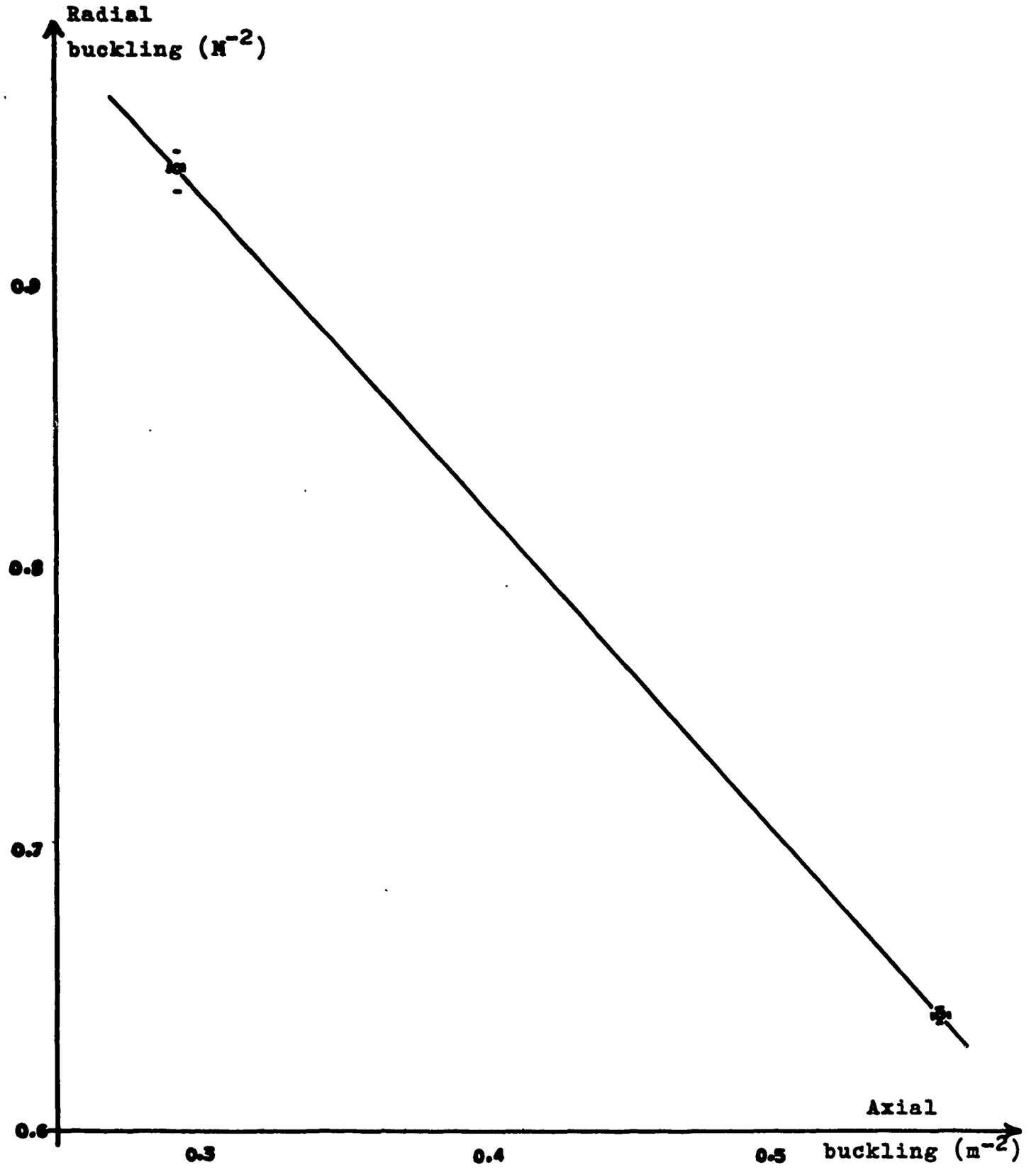

Fig 12 - Anisotropy of the reference lattice at the 224 mm pitch

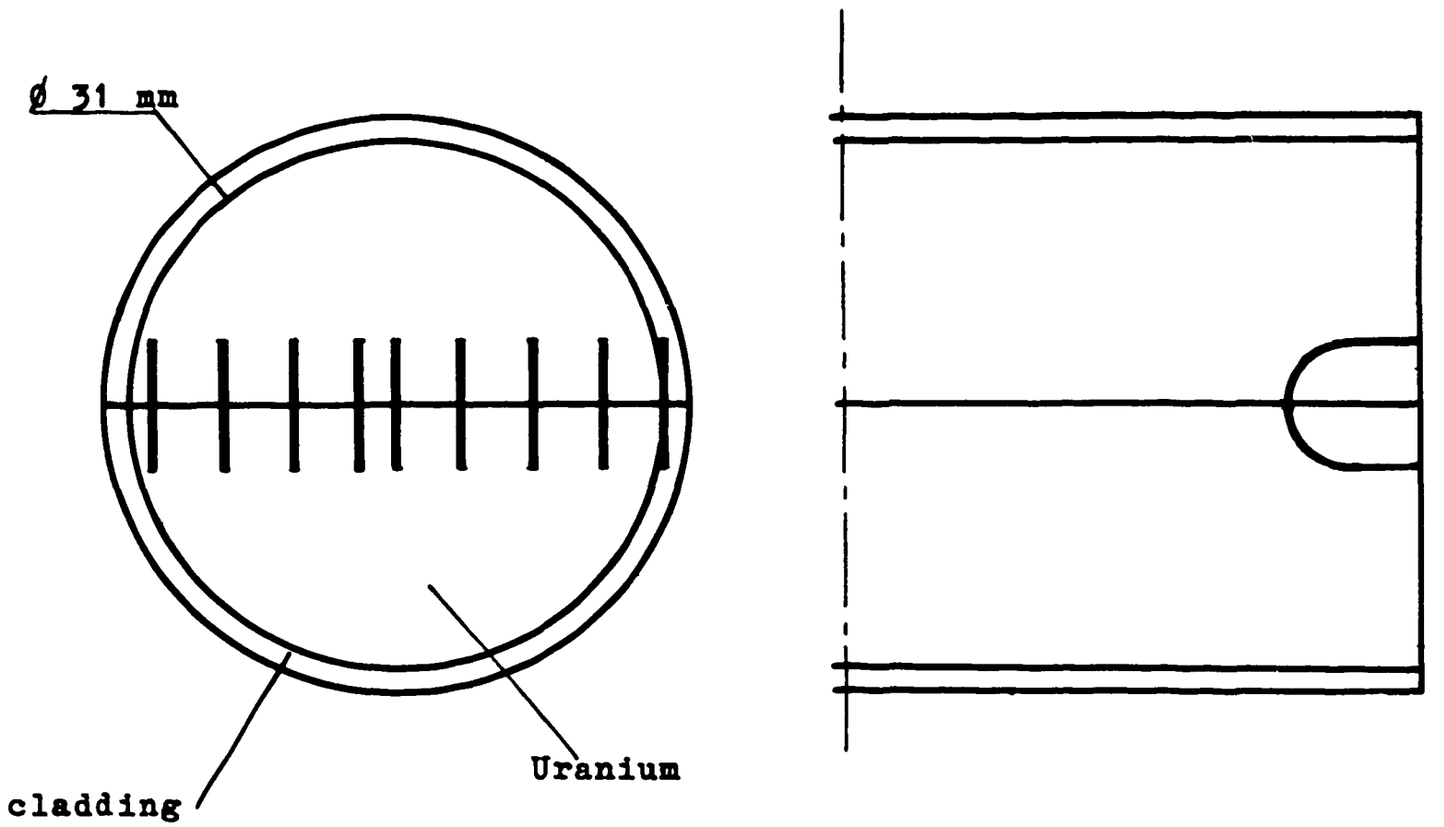

Fig 13 - Fuel element for fine structure experiments

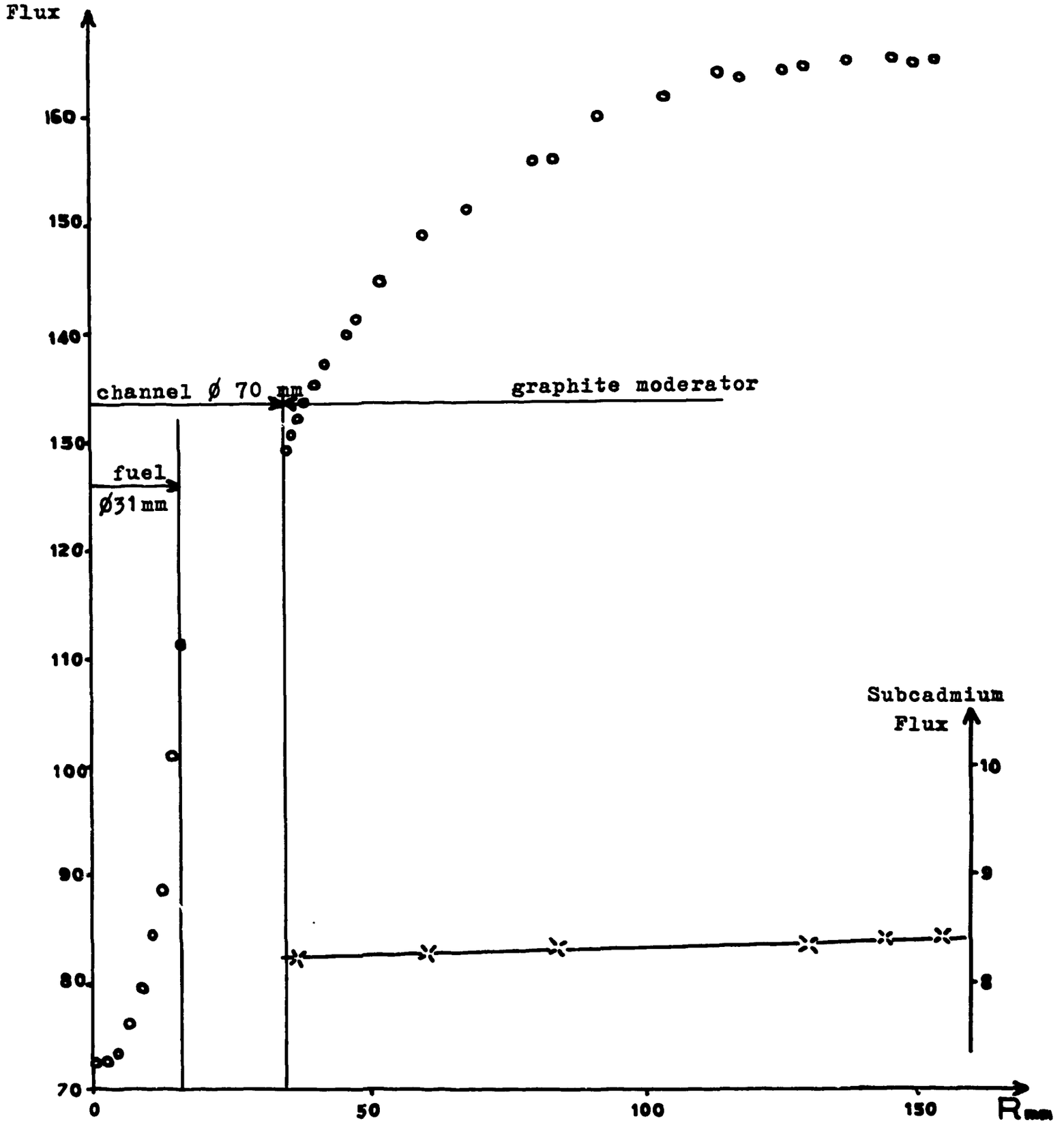

Fig 14 - Fine structure experiment - Pitch:224mm
Channel diameter: 70mm
fuel diameter: 31mm

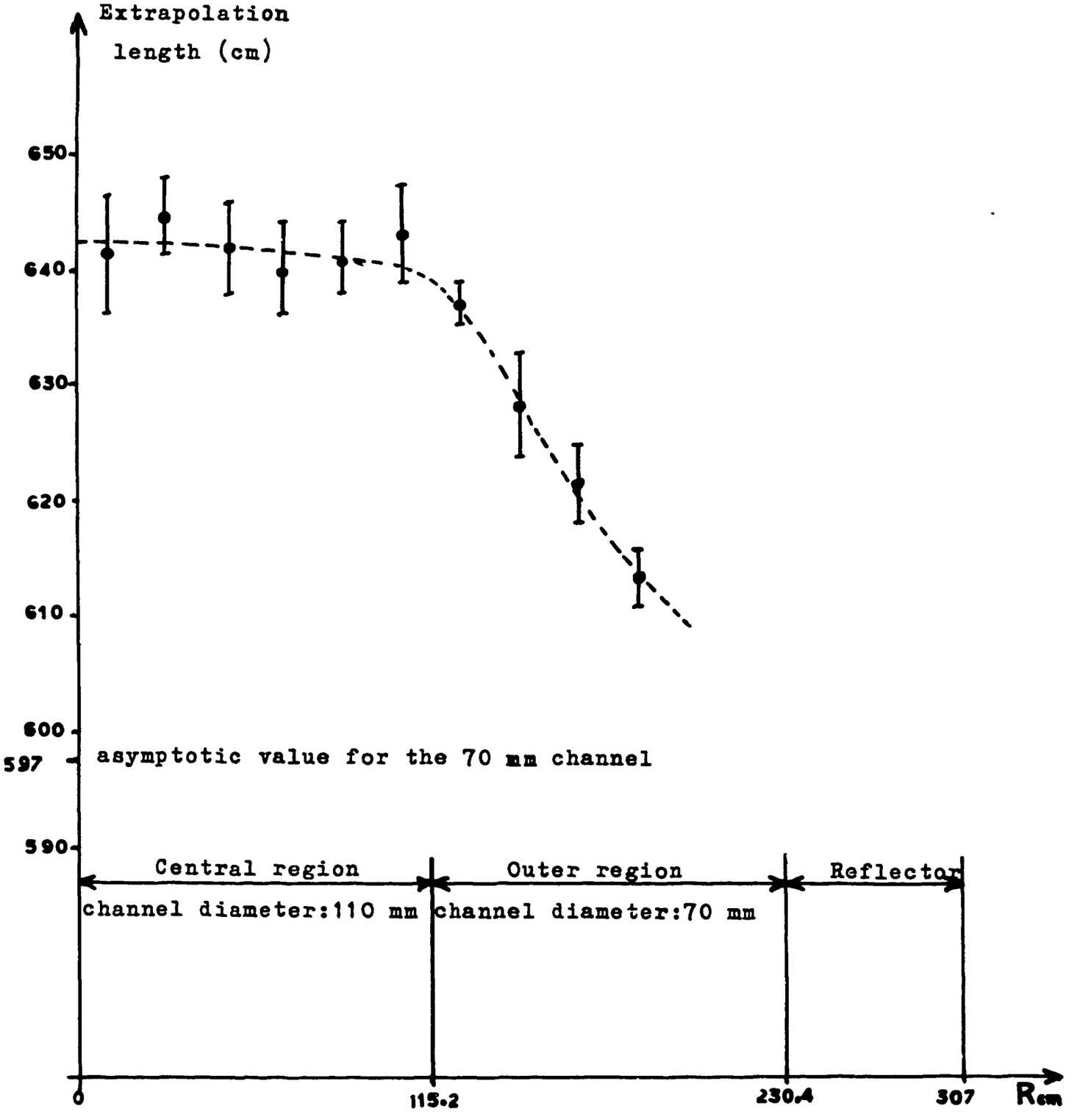

Fig 15 - Change in axial extrapolation length

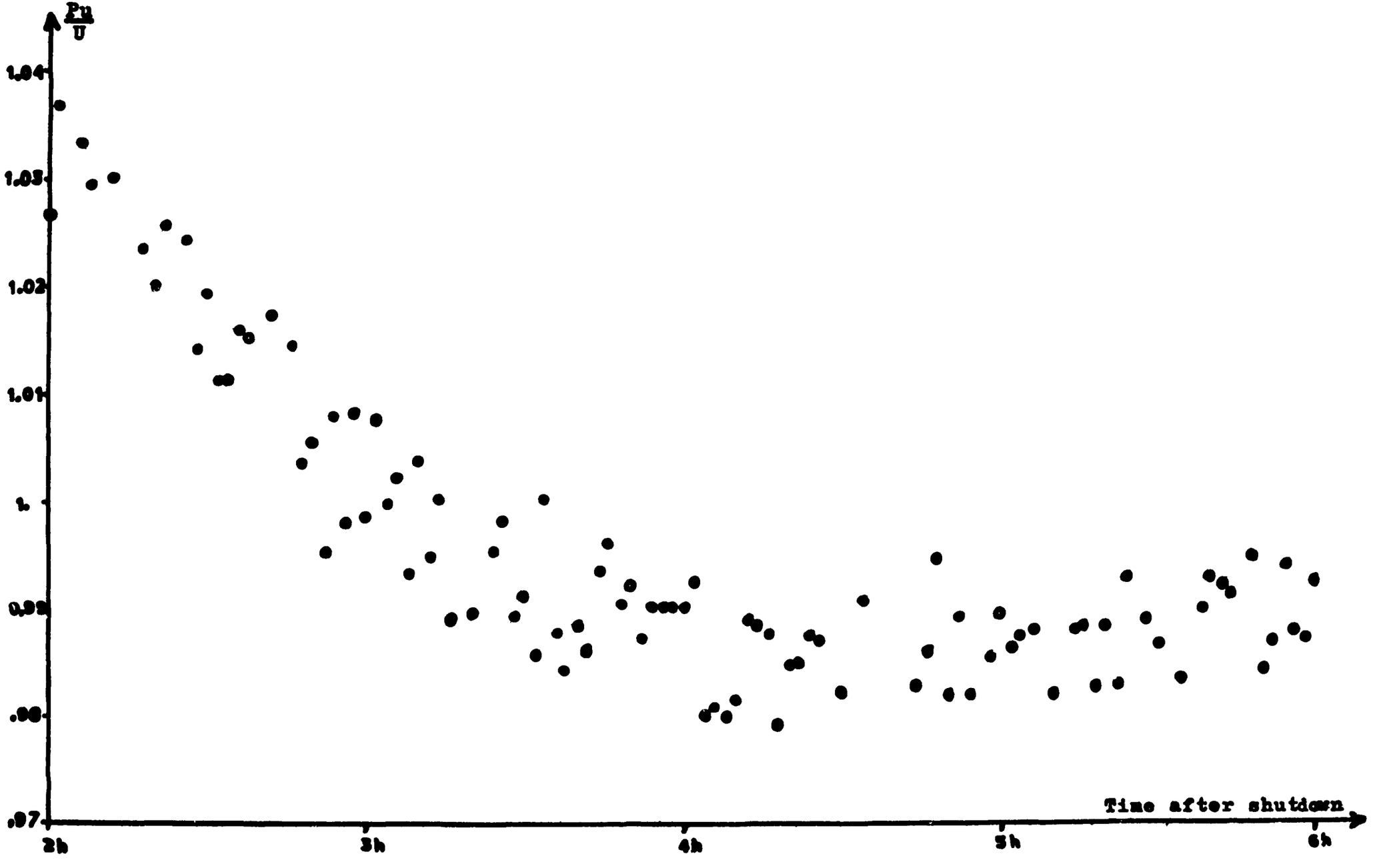

Fig 16 - Time dependance, after shutdown, of the $^{Pu}/_{U}{}^{49}{}_{25}$ activation ratio

FIN