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1. INTRODUCTION AND SUMMARY

In the framework of the Cooperation Agreement N° 150-75 PIPGD among the Commission of the European Communities, the Kernkraftwerk RWE-Bayernwerk GmbH (KRB) and the Kraftwerk Union AG Frankfurt (KWU) a programme of post-irradiation analyses of the fuel assemblies B23 and C16 unloaded from the Gundremmingen Reactor at the end of the fifth irradiation cycle, was carried out in the Ispra and Karlsruhe Establishments of the Joint Research Centre.

The main objective of the programme was the measurement of the burn-up and isotopic composition of selected fuel samples in order to obtain a set of data to be used for checking the accuracy of nuclear code calculations.

The other objective of the programme was the metallographic analysis of the UO_2 fuel and of the zircaloy cladding.

In the LMA laboratory of the Ispra Establishment ten fuel rods were subjected to optical inspection, metrology, mechanical tests on the fuel cladding and metallography. The results obtained will be the subject of a separate report.

Gamma scanning measurements on the fuel rods and gamma spectrometry measurements were also carried out on the selected rod positions.

Fuel samples chosen for radiochemical analyses were cut from the rods at 440 mm and 2680 mm from the bottom of the fuel stack.

The samples were dissolved in the laboratories of Ispra and Karlsruhe and aliquots of the solutions were subjected to radiochemical processes and to gamma, mass and alpha spectrometry determinations. Gamma spectrometry was mainly used to determine the ^{137}Cs activity, from which the burnup was derived.

Mass spectrometry, combined in some cases with isotope dilution techniques, was used to determine the concentrations

and/or the isotopic compositions of uranium, plutonium, americium, of neodymium and of the krypton and xenon fission gases.

Alpha spectrometry was used to determine the concentrations of some nuclides of plutonium, americium and curium. The concentration of ^{148}Nd was then also used for the evaluation of the burn-up.

In section 3.1. all the original data of the gamma, mass and alpha determinations are reported. These data were processed in order to derive values of burn-up and of isotopic composition, build up and depletion of heavy isotopes, which are reported in section 3.2. The nuclear data used in the processing of experimental values are listed in section 3.2.2.

The availability of the original experimental data, reported in section 3.1., also allows those interested to apply a data processing based on different nuclear data or different assumptions.

In order to check the accuracy of the values of burn-up and isotopic composition measured in our experiments three procedures were applied:

- Use of different methods in the measurement of the same quantity : this procedure was applied for the burn-up values which were determined both from ^{137}Cs and ^{148}Nd.
- Comparison between the results of different laboratories : this procedure was applied by analysing 4 pairs of adjacent pellets in the laboratories of Ispra and Karlsruhe.
- Use of the isotope correlation approach (see section 3.3.).

Similar programmes of post-irradiation examination had been carried out on the fuel discharged from the Trino Vercellese reactor, operated by ENEL, after the 1st and the 2nd irradiation cycles (1,2).

2. FUEL CHARACTERISTICS AND SELECTION OF FUEL SAMPLES

The Gundremmingen Nuclear Power Plant, operated by KRB, is equipped with a dual cycle boiling water reactor rated at 250 MW (e).

Two fuel assemblies were chosen for examination : fuel element B23 whose irradiation started on the 25th August 1969 and finished on the 5th May 1973, and fuel element C16 whose irradiation started on the 25th July 1970 and finished on the 5th May 1973.

The main characteristics of the Gundremmingen reactor core are given in Table 1. More detailed information can be found in Reference 3.

In Table 2 the irradiation history of the fuel elements B23 and C16 is shown.

The fuel assemblies B23 and C16 selected for post-irradiation analyses were composed by 29 rods with initial enrichment of 2.53W% in ^{235}U and by 7 rods with initial enrichment of 1.87W% in ^{235}U. B23 reached an average burn-up of 22,600 MWD/MTU while C16 reached an average burn-up of 17,100 MWD/MTU. The main characteristics of the fuel assemblies are reported in Table 3.

Schematic maps of the reactor core indicating the positions of the selected fuel assemblies during the various irradiation cycles are given in Figure 1.

Figure 2 shows the locations in the assemblies of the fuel rods selected for the measurements.

Figure 3 schematically shows the positions of the elements B23 and C16 in respect to the control rod during the different irradiation cycles.

Table 4 indicates the position in which the fuel rods were irradiated, the locations of the fuel pellets analysed, the laboratories (Ispra and Karlsruhe) where the analyses of the various fuel sections were carried out.

All the fuel section were cut at 2680 mm from the bottom of the stack, in the steam-water zone, having an average void fraction of about 50%.

Only rod A1 was cut also at 440 mm from the bottom, in the water phase. The two different cutting levels of rod A1 are indicated in this work as:

A1(1) the sample cut at 440 mm level

A1(2) the sample cut at 2680 mm level

3. DETERMINATION OF BURN-UP AND ISOTOPIC COMPOSITIONS

3.1. Experimental Procedures

A total of ten fuel rods belonging to both B23 and C16 assemblies were subjected to non-destructive gamma spectrometry measurements in the LMA laboratory to determine the ^{137}Cs activity.

In the selected position (see Table 4) six rods of the fuel assembly B23 and four rods of the fuel assembly C16 were cut and samples, 10 mm thick, were prepared for radiochemical analysis. The cutting positions were determined with an uncertainty of $\pm$ 3 mm. The fuel samples were dissolved in nitric acid in hot cells. Small aliquots of the fuel solutions, which can be handled without heavy shielding, were transferred to glove-boxes for radiochemical processes. In the Karlsruhe laboratory the fission gases were collected during the fuel sample dissolution.

The analyses were performed at Ispra (10 samples) and Karlsruhe (2 samples + 4 for cross checking).

Radioactive fission products were determined by gamma spectrometry, ^{148}Nd, plutonium and uranium nuclides were determined by isotopic dilution and mass spectrometry. The isotopic composition of the fission gases krypton and xenon was determined by mass spectrometry. ^{236}Pu, ^{238}Pu, ^{241}Am, ^{242}Cm, and ^{244}Cm were determined by alpha spectrometry.

In the present work a short description of the experimental procedures adopted at Ispra and Karlsruhe is given. These procedures are described in detail in ref. (1,2,4,5).

3.1.1. Gamma spectrometry

Gamma spectrometry measurements were carried out both on the entire fuel rods to determine the ^{137}Cs activity and on the fuel solutions to determine the activities of ^{137}Cs, ^{134}Cs, and ^{154}Eu.

Non-destructive and destructive measurements of ^{137}Cs were used to evaluate the burn-up of the fuel samples. The measurements of ^{134}Cs and ^{154}Eu were used to check other experimental determinations (burn-up and isotopic compositions) by means of the isotope correlation technique.

a) The measurements on the entire fuel rods were carried out with a coaxial type Ge(Li) detector having a FWHM of 2.6 KeV at 1332 KeV of ^{60}Co, connected to an Intertechnique PLURIMAT 20.

   They were performed on the position at 2680 mm from the bottom for nine rods at 440 mm from the bottom for three rods and also at 1750 mm from the bottom for one rod.

   The standard deviation of the measurements was about 2.0%.

b) The measurements on fuel solutions were carried out with a coaxial type Ge(Li) detector, having a FWHM of 2.3 KeV at 1332 KeV of ^{60}Co, connected through a preamplifier and amplifier to a minicomputer LABEN 701.

   The standard deviation for ^{134}Cs and ^{137}Cs was about 1.5%, while the standard deviation for ^{154}Eu was about 5%.

Further details of measurement techniques are given in References 1 and 2.

Six fuel pellets, four of which were adjacent to those anal y ed at Ispra, were examined at the Karlsruhe JRC Establishment. All the results obtained at Karlsruhe (4) and the data

obtained at Ispra for ^{137}Cs, ^{134}Cs and ^{154}Eu expressed as dis/sec/g of final uranium at reactor shut-down are reported in Table 5. The agreement between the ^{137}Cs data of the two laboratories can be considered quite satisfactory. Fission products diffusion was detected by gamma-scanning at the cutting position of the rod E5 of the C16 assembly. Similar diffusion was also detected on the samples A1 (1), A1 (2) and E3 of the B23 assembly and on the samples A1 (2) and C5 of the C16 assembly.

3.1.2. Radiochemical Procedures

The purpose of the radiochemical processes is to obtain from the original fuel solution, purified samples of uranium, plutonium, americium and neodymium to be analyzed by mass and alpha spectrometry. Part of the purification processes was carried out after an isotopic dilution step. At Ispra uranium and plutonium were individually purified by means of solvent extraction techniques (2). At Karlsruhe an ion--exchange technique was used to reduce the ratio between uranium and plutonium and to purify both the elements in the same step. At Ispra the neodymium and americium purification procedure, which is described, was slightly modified and improved in respect to the one used for Trino Vercellese reactor fuel samples.

Neodymium and americium purification

Known aliquots of the sample solution (1 - 2 /ug of ^{148}Nd, dissolved in 7 M HNO_3) and of the spike solution (about 1 /ug of ^{150}Nd) were mixed, evaporated to dryness and the residue dissolved in 9.5 M HCl.

The solution was loaded onto a column, 0.5 cm internal diameter, filled with 0.6 g DOWEX 1 x 8 (200 - 400 Mesh) resin in order to separate the rare earths from the bulk of the most important gamma-ray emitters. The flow-rate was about 1 ml/min. Uranium, plutonium and fission products remained fixed on the resin and the rare earths were eluted with 9.5 M HCl.

The solution containing rare earths and transplutonium elements was evaporated to dryness and the residue dissolved in 0.05 M hydrochloric acid. Selective separation of neodymium from its neighbouring rare earths was carried out utilising the method described by L. Koch and coworkers (5). The 0.05 M HCl solution was percolated through a DOWEX 50 x 8 (200 - 400 mesh) resin column (0.3 cm internal diameter and 6.5 cm long) with a flow rate of 0.20 ml/min. The column was then washed with 0.05 M HCl and water. Rare earths were then eluted with 0.05 M alpha-hydroxyisobutyric acid at pH = 4.6.

In such conditions, being the americium eluted just before the neodymium, both the elements were collected in the same fractions.

In order to eliminate the alpha-hydroxyisobutyric acid the fraction containing Am and Nd was added with an equal volume of 14 M HNO_3, then evaporated to dryness.

The elimination of possible traces of organic products was performed by heating the residue in a oven at 500 - 600°C. One or two drops of 14 M HNO_3 were then added. The operation was repeated twice if traces of organic materials were still present.

The residue was then redissolved in 1 M HNO_3 in order to have a suitable solution for mass spectrometric analyses.

A total of six samples were purified for each dissolved cross section : three unspiked and three ^{150}Nd spiked.

3.1.3. Mass Spectrometry

At the Ispra laboratory mass spectrometric measurements were performed on uranium, plutonium and neodymium, using a micromass type VG 30 A spectrometer equipped with thermal ionization triple-filament sources.

For each fuel sample, three spiked and three unspiked, independently purified solutions of U, Pu and Nd, were prepared. In general, the third solution of each group was analised

only in case of a poor agreement in the results; for each fuel sample two mass spectrometric runs for the different types of solutions were normally carried out. Finally, for each run at least ten scans of the isotopes group were executed.

Corrections have been introduced for mass-discrimination effects as determined by isotopic standards of the National Bureau of Standards (USA).

The atom ratios for uranium and plutonium are reported in Table 6 with the date of the measurement.

The average standard deviations of the measurements of the different isotopic ratios are given in Table 7.

The concentration of uranium and plutonium nuclides have been determined by means of isotopic dilution techniques, using as spiking isotopes, ^{233}U and ^{242}Pu. The spike solutions were calibrated against weighed solutions prepared with pure material supplied by the National Bureau of Standards. The total error in the determination of the concentrations of uranium and plutonium is about 0.5%. This error includes the uncertainties due to the isotope dilution procedures.

The concentration of ^{148}Nd was determined again by the isotopic dilution technique with ^{150}Nd as a spike. A correction has been introduced for the contamination due to natural neodymium on the basis of the determination of ^{142}Nd.

The presence of ^{142}Ce and ^{150}Sm has been verified and suitably corrected. The spike solution of ^{150}Nd has been calibrated against a natural neodymium supplied by the Central Bureau of Nuclear Measurements in Geel. The total error in the determination of ^{148}Nd, inclusive of the uncertainties due to the isotope dilution procedures, is about 1%.

The $^{148}Nd/^{238}U$, the $^{137}Cs/^{238}U$ and $^{239}Pu/^{238}U$ atom ratios and the total Pu/U mass ratio are reported in Table 8.

The Karlsruhe laboratory also performed isotopic composition measurements by mass spectrometry on the krypton and xenon fission gases.

The results of these measurements are reported in Table 9. Their average standard deviations are reported in Table 7.

A detailed comparison between the results obtained at Ispra and Karlsruhe is presented in section 3.3.

3.1.4. Alpha spectrometry

The alpha spectrometry measurements were carried out at the Ispra and Karlsruhe laboratories. Without any chemical treatment, an aliquot of fuel solution containing about 0.01 mg of uranium was dropped onto a tantalum counting plate.

The alpha spectra were obtained by means of a semiconductor silicon detector, connected, through an amplifier either to a multichannel analyzer or to a LABEN 701 small computer.

Since the alpha-decay energies partly overlap, only the activity ratios:

$$\frac{^{238}Pu + ^{241}Am}{^{239}Pu + ^{240}Pu}, \quad \frac{^{242}Cm}{^{239}Pu + ^{240}Pu}, \quad \frac{^{244}Cm}{^{239}Pu + ^{240}Pu}$$

were determined.

For each fuel sample solution two sources were prepared and each source counted two or three times. The standard deviations of the measurements of the alpha activity ratios are between 2 and 5%.

Samples purified for mass spectrometry also served for the measurement of the activity ratios :

$$\frac{^{238}Pu}{^{239}Pu + ^{240}Pu} \quad \text{and} \quad \frac{^{236}Pu}{^{239}Pu + ^{240}Pu}$$

The average relative standard deviation for the measurement of the $^{238}Pu/(^{239}Pu + ^{240}Pu)$ ratio is about 1%, while that

for the ratio $^{236}Pu(^{239}Pu + ^{240}Pu)$ is about 10%. This is due to the very small quantity of ^{236}Pu present in the samples and consequently to the very low counting rate.

The estimated uncertainty in the determination of $\frac{^{241}Am}{^{239}Pu + ^{240}Pu}$ is about 10%.

The results of alpha spectrometry measurements carried out at Ispra and Karlsruhe laboratories, are reported in Table 10.

3.2. Processing of the experimental data

3.2.1. Burn-up determination by the ^{148}Nd and ^{137}Cs methods

The processing of the rough analytical data in order to obtain the burn-up from ^{148}Nd or ^{137}Cs atom content of the samples, has been extensively illustrated in previous reports [1,2,4,5,11].

In the present work only a few remarks are done concerning the updated nuclear data used.

The ^{148}Nd amount measured has been corrected to take into account:

a) the ^{148}Nd burn out by neutron capture. Correction factors not higher than 1% (0.5 ÷ 1.0% for different burn-up levels) have been applied

b) the ^{148}Nd build up from ^{147}Nd capture. The amount of the correction (1.0 ÷ 1.5 % according to the different burn-up levels) has been evaluated on the basis of a work by Maek et al. (6) in which the value of the activation cross-section of ^{147}Nd is suggested as

$$\sigma_c^{147} = 440 \pm 150 \text{ b}$$

The measured ^{137}Cs has also been corrected for in-pile decay, applying correction factors of the order of 5.0% (4.5 ÷ 5.5% according to the irradiation histories).

The burn-up has also been evaluated from the non-destructive ^{137}Cs measurements already referred to (see 3.1.1.).

The ^{137}Cs activity values measured have been converted to burn-up by means of a calibration curve obtained by using four burn-up values derived from ^{148}Nd measurements carried out at the Karlsruhe laboratory, as indicated in Table 11.

The following correlation has been established:

$$Y = 2.21\ X - 281$$

where : Y = MWD/MTU
X = counts/min ^{137}Cs measured at the fuel rod.

The correlation coefficient of the regression equation has been in this particular case, better than 0.999 and the standard error of the regression line has been evaluated as:

143 MWD/MTU

This equation has been considered as a calibration line for the determination of other burn-up values.

The procedure used at Karlsruhe for burn-up determination from ^{137}Cs measurements is different because the ratio between ^{137}Cs and initial uranium weight is directly determined. This procedure is described in reference (4).

The burn-up values determined at Ispra and Karlsruhe from ^{148}Nd and ^{137}Cs are reported in Table 11.

3.2.2. Nuclear data

The average fission yields calculated for ^{148}Nd and ^{137}Cs at different burn-up levels, using the nuclear data of Table 12 (7,8) and the fission fractions for the various nuclides at different burn-up, supplied by KWU, are the following:

MWD/MTU	^{148}Nd average fission yield	^{137}Cs average fission yield
12,500	1.744×10^{-2}	6.430×10^{-2}
17,500	1.751×10^{-2}	6.470×10^{-2}
22,500	1.759×10^{-2}	6.499×10^{-2}
27,500	1.767×10^{-2}	$6,524 \times 10^{-2}$

In order to keep the error introduced in burn-up evaluation at a negligible level with respect to the experimental one, we have adopted the following average fission yields:

- for burn-up values up to 20,000 MWD/MTU (fuel assembly C16)

  $Y_{^{148}Nd} = 1.747 \times 10^{-2}$ $\quad$ $Y_{^{137}Cs} = 6.450 \times 10^{-2}$

- for burn-up values higher than 20,000 MWD/MTU (fuel assembly B23)

  $Y_{^{148}Nd} = 1.763 \times 10^{-2}$ $\quad$ $Y_{^{137}Cs} = 6,512 \times 10^{-2}$

Using the energy release per fission of Table 12 and the values of fission fractions given by KWU, the following average values of MeV/fission have been calculated at different burn-up levels:

MWD/MTU	MeV/fission (average value)
12,500	205.76
17,500	206.56
22,500	207.23
27,500	207.83

Due to the small differences among the average values at different burn-up levels, the value of 206.8 MeV/fission has been used for all the samples.

The half-lives of Pu, Am and Cm isotopes utilized in this work are those reported in Reference 2.

3.2.3. Determination of Isotopic Composition, Build up and Depletion of Heavy Isotopes

From the mass spectrometry data (Table 6) the isotopic composition of uranium was calculated and presented in Table 13.

The isotopic compositions of plutonium presented in Table 14 (atom %) was calculated from the mass spectrometry data (Table 6) and alpha spectrometry data (Table 10) which were combined using simple equations.

The heavy isotope data were also processed in order to obtain the build up and depletion of the different isotopes.

The build up and depletion of U, Pu, Cm and Am isotopes, in atoms are presented in Tables 15, 16 and 17.

3.3 Analysis of the Accuracy of the Values of Burn-up and Isotopic Composition

The evaluation of the accuracy of the experimental values of burn-up and isotopic composition was carried out following three different procedures:

- The burn-up values were determined by means of two different techniques. A comparison between independently determined burn-up values provides a check of the validity of the results.
- Four pairs of adjacent fuel sections were analyzed at Ispra and Karlsruhe. Comparison between the results of the two laboratories provides a check of the validity of the values of burn-up and isotopic composition.
- Isotope correlations between different nuclides in irradiated fuels and between nuclides and burn-up have been extensively used (1,4,10,11,12,13,14).

3.3.1. Comparison Between Burn-up Values Determined by Different Experimental Techniques

The total error in the determination of the burn-up values can be evaluated by combining the statistical errors of the measurements, and the nuclear data uncertainties are reported in Table 7.

A comparison between the burn-up values obtained from ^{148}Nd and ^{137}Cs is presented in Table 11.

The values derived from ^{137}Cs are generally higher than those derived from ^{140}Nd.

The average difference between the values obtained at Ispra from ^{137}Cs and ^{148}Nd is 2.3%.

The ^{137}Cs measurements performed at Karlsruhe present, on the contrary, a larger discrepancy.

The agreement between the burn-up values from ^{137}Cs measured at Ispra and Karlsruhe for three pairs of adjacent fuel sections is about 2.3%.

Samples in which a migration of fission products was evidenced by gamma scanning were not considered in the comparison.

In the same Table 11 the comparison between burn-up values determined from destructive and non-destructive measurements of ^{137}Cs is also presented.

The samples in which a cesium migration was detected were not considered in this comparison. The average difference between the two sets of data is about 4.4%.

3.2.2. Comparison Between Values of Isotopic Composition, Build up and Depletion of Heavy Isotopes Determined at Ispra and Karlsruhe

The statistical errors in the determination of atom ratios by mass spectrometry and of activity ratios by alpha spectrometry, expressed as standard deviations of the measurements, were reported in section 3.1.

The systematic errors in these determinations are much more difficult to evaluate.

However we consider that the comparison between the results obtained in different laboratories is a very effective tool for the evaluation of the total error in the measured quantities.

The average differences between the values measured at Ispra and Karlsruhe for the four pairs of adjacent pellets, are presented in Table 18.

The agreement between the two laboratories in the determination of the uranium and plutonium isotopes is excellent. The agreement in the determination of ^{242}Cm and ^{244}Cm is also very satisfactory

3.3.3. Isotope correlations

A consistency check of the most important quantities determined by the post-irradiation analyses has been attempted by means of the isotope correlation technique.

Both spectrum independent and dependent correlation could serve to test the experimental data and/or to obtain answers on the physical behaviour of cell parameters.

In the Fig. 4 the Pu/U mass ratio is plotted against the uranium depletion

$$D_5 = \frac{W_o^5 - W^5}{W_o^5}$$

where W_o^5 and W^5 are the percentage weight of ^{235}U in the fresh and irradiated fuel.

The different lines drawn show the different Pu production rates of the various fuel rods, according to the spectrum hardening towards the inner cluster zones.
The different samples correlate coherently with their position in the fuel element, apart sample B4 which perhaps should have been closer to the B3 line.

The discussion of the analytical post-irradiation data is difficult due to the channel complex spectrum structure present.

An important dispersion of the lines was expected, because of the poor correlation between ^{239}Pu (55-65% of the total Pu) which is a ^{238}U resonance capture product, and the parameter D_5 linked with the capture cross-section of ^{235}U, which is less dependent from the spectrum structure.

These facts determine the strong dependence of the correlation Pu/U against D_5 from the radial position (e.g. from the spectrum structure) in the cluster.

Similar conclusions may be drawn from Fig. 5 where the build up of Plutonium isotopes is plotted against the burn-up: again the ^{239}Pu data lay on quite dispersed lines, according to their radial positions.

^{235}U and ^{239}Pu fissions are the major contributors to burn-up and their fission cross-sections are less sensitive to the spectrum shifts then ^{238}U capture cross-section.

The ^{240}Pu and ^{242}Pu build up, also shown in Fig. 5, are less spectrum dependent parameters being capture products of ^{239}Pu and ^{241}Pu respectively. Capture cross-sections of these two isotopes have, in fact, an important thermal part and a relatively low resonance structure.

The above considerations suggest the conclusion that even Pu isotopes are better correlated with burn-up (15) while odd Pu isotopes correlate better with Pu/U (see Fig. 6).

In Fig. 7 the $^{235}U/^{238}U$ mass ratio is plotted against the burn-up obtained by the ^{148}Nd technique.

It can be observed that also for this correlation the experimental points are grouped on different straight lines according to their radial position in the cluster. Moreover the points relevant to the two fuel elements can be apparently grouped on different lines. This fact could be explained with the different irradiation history of the two fuel assemblies.

The ratio $^{236}U/^{238}U$ against D_5 is presented in Fig. 8. The experimental points are not too much dispersed and it resulted practically impossible to separate them according to their radial position.

In Fig. 9 the ratio $^{240}Pu/^{239}Pu$ is plotted against $^{235}U/^{238}U$; also in this case the two parameters are quite strictly correlated and show their relative independence from spectrum variation.

The burn-up is plotted vs. three different fission product ratios in Figg. 10, 11 and 12.

The most spectrum dependent among the three indicators seems to be the $^{134}Cs/^{137}Cs$ ratio (Fig. 10) while ratios $^{132}Xe/^{131}Xe$ and $^{83}Kr/^{84}Kr$ appear better correlated with the burn-up.

In Figg. 13 and 14 the ^{242}Cm and ^{244}Cm production at various burn-up levels are also presented.

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TABLE 1 - Core Mechanical Data

CORE	
Equivalent diameter	274.8 cm
Active height	330.2 cm
Number of square fuel assemblies	368
Initial enrichments	1.68 - 2.34%
Number of control rods	89
UO_2 in square fuel assemblies	52,982 Kg
Total U weight	46,703 Kg
SQUARE FUEL ASSEMBLY	
Rod array	6 x 6
Number of fuel rods	36
Side of square fuel section	11.352 cm
Total lenght	386.1 cm
Channing material	Zry - 4
UO_2 weight	144.0 Kg
FUEL PELLET (both dished and undished)	
UO_2 average density	10.5 g/cm^3
Diameter	12.24 mm
Length of pellet stack in fuel rod	330.2 cm
Clad-pellet clearance	0.1375 mm
Temperature	650°C
FUELD CLAD	
Inside diameter	12.5 mm
Wall thickness	0.889 mm
Material	Zry - 2
CONTROL ROD (cruciform)	
Absorbing material	B_4C - powder
Absorber length	325.0 cm
MODERATION AND COOLING	
Inlet temperature	266°C
Outlet temperature	286°C
Pressure	69 bar

TABLE 2 - Irradiation History of the Fuel Elements B23 and C16

Cycle of operation	Periods	Days	CORE BURN-UP (MWD/MTU)	
			Fuel element B23	Fuel element C16
SECOND	25.08.69 30.05.70	279	5,839	
SHUT DOWN	31.05.70 24.07.70	56	-	
THIRD	25.07.70 12.06.71	323	6,131	5,959
SHUT DOWN	13.06.71 15.07.71	33	-	-
FOURTH	16.07.71 30.04.72	290	5,483	5,083
SHUT DOWN	01.05.72 30.06.72	61	-	-
FIFTH	01.07.72 05.05.73	309	5,174	6,026

TABLE 3 - Characteristics of the Fuel Assemblies

	Fuel element B23	Fuel element C16
Fuel material	enriched UO_2	enriched UO_2
Initial enrichment in ^{235}U	1.87 + 2.53 W%	1.87 + 2.53 W%
Final burn-up	22,627 MWD/MTU	17,068 MWD/MTU
- During second cycle	5,839 MWD/MTU	
- During third cycle	6,131 MWD/MTU	5,959 MWD/MTU
- During fourth cycle	5,483 MWD/MTU	5,083 MWD/MTU
- During fifth cycle	5,174 MWD/MTU	6,026 MWD/MTU
Core positions :		
- Second cycle	H - 4	
- Third cycle	H - 4	J - 9
- Fourth cycle	H - 4	J - 9
- Fifth cycle	J - 4	E - 7
Pellet	undished	dished

TABLE 4 : SELECTED FUEL SAMPLES

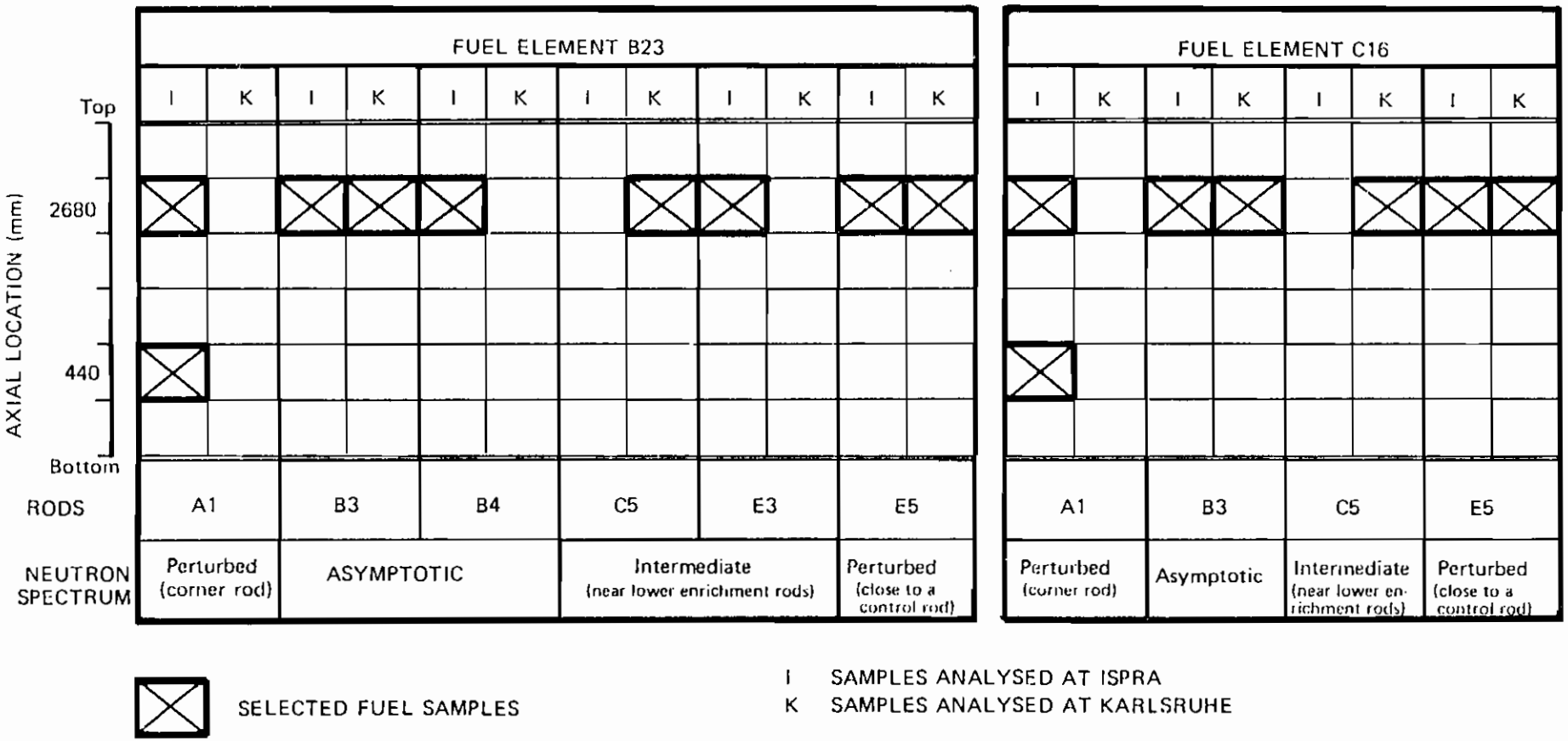


TABLE 5 - Specific Activities of Fission Products

dis/sec/g U final at Reactor Shut Down

Fuel Assembly	Sample	Laboratory	^{137}Cs ($\times 10^{9}$)	^{134}Cs ($\times 10^{9}$)	^{154}Eu ($\times 10^{8}$)	$\frac{^{134}Cs}{^{137}Cs}$	$\frac{^{154}Eu}{^{137}Cs}$ ($\times 10^{-2}$)
B 23	A1 (1)	Ispra	3.66	3.49	1.79	0.954	4.892
	A1 (2)	Ispra	2.89	3.28	1.80	1.133	6.218
	B3	Ispra	2.61	2.57	1.55	0.984	5.934
		Karlsruhe	2.67				
	B4	Ispra	2.70	2.94	1.49	1.089	5.519
	C5	Karlsruhe	3.07				
	E3	Ispra	2.75	3.00	1.53	1.091	5.564
	E5	Ispra	3.08	3.25	1.61	1.055	5.227
		Karlsruhe	3.24				
C 16	A1 (1)	Ispra	2.55	2.26	0.89	0.887	3.479
	A1 (2)	Ispra	2.69	2.85	1.09	1.058	4.047
	B3	Ispra	1.83	1.45	0.75	0.791	4.106
		Karlsruhe	1.91				
	C5	Karlsruhe	2.20				
	E5	Ispra	1.92	1.63	0.84	0.849	4.380
		Karlsruhe	2.32				

TABLE 6 - Atom Ratios of U and Pu from Mass Spectrometry

			U ($\times 10^{-2}$)		Pu ($\times 10^{-1}$)			
Fuel Assembly	Sample	Laboratory	$\frac{235}{238}$	$\frac{236}{238}$	Date of measurem.	$\frac{240}{239}$	$\frac{241}{239}$	$\frac{242}{239}$
B 23	A1 (1)	Ispra	0.676	0.346	12.03.76	4.883	1.872	0.901
	A1 (2)	Ispra	0.727	0.349	18.03.76	4.407	1.971	0.864
	B3	Ispra	1.029	0.311	03.11.75	3.448	1.470	0.418
		Karlsruhe	1.049	0.312	18.05.76	3.446	1.430	0.414
	B4	Ispra	0.960	0.319	05.10.76	3.684	1.459	0.466
	C5	Karlsruhe	0.905	0.332	19.05.76	3.970	1.560	0.536
	E3	Ispra	0.914	0.331	01.10.76	3.819	1.497	0.505
	E5	Ispra	0.707	0.344	09.12.75	4.671	1.793	0.756
		Karlsruhe	0.725	0.352	19.05.76	4.667	1.750	0.749
C 16	A1 (1)	Ispra	0.916	0.323	29.09.76	4.047	1.420	0.496
	A1 (2)	Ispra	1.048	0.305	01.10.76	3.445	1.459	0.450
	B3	Ispra	1.375	0.256	02.03.76	2.501	1.025	0.192
		Karlsruhe	1.382	0.258	30.04.76	2.489	1.006	0.188
	C5	Karlsruhe	1.306	0.262	30.04.76	2.780	1.059	0.222
	E5	Ispra	1.087	0.284	06.11.75	3.492	1.300	0.375
		Karlsruhe	1.111	0.291	03.05.76	3.472	1.242	0.342

TABLE 7 - Average Standard Deviations of the Measurements

ISOTOPIC RATIOS OF U AND Pu	
$^{235}U/^{238}U$	0.7 %
$^{236}U/^{238}U$	1.2 %
$^{240}Pu/^{239}Pu$	0.4 %
$^{241}Pu/^{239}Pu$	0.6 %
$^{242}Pu/^{239}Pu$	0.7 %

ISOTOPIC RATIOS OF FISSION GASES			
$^{83}Kr/^{86}Kr$	0.3 %	$^{131}Xe/^{134}Xe$	0.2 %
$^{84}Kr/^{86}Kr$	0.2 %	$^{132}Xe/^{134}Xe$	0.2 %
$^{84}Kr/^{83}Kr$	0.3 %	$^{136}Xe/^{134}Xe$	0.2 %
		$^{132}Xe/^{131}Xe$	0.2 %

BURN-UP DETERMINATION	
^{148}Nd	2 %
^{137}Cs (destructive)	4 %
^{137}Cs (non-destructive)	5 %

TABLE 8 - Atom ratios of Neodymium, Cesium and Plutonium referred to final Uranium

Fuel Assembly	Sample	Laboratory	$\frac{^{148}Nd}{^{238}U}$ (a) ($\times 10^{-4}$)	$\frac{^{137}Cs}{^{238}U}$ (a) ($\times 10^{-3}$)	$\frac{^{239}Pu}{^{238}U}$ ($\times 10^{-3}$)	Total Pu/U Mass ratio ($\times 10^{-3}$)
B 23	A1 (1)	Ispra	4.88	2.12	3.89	6.98
	A1 (2)	Ispra	5.22	1.67	4.99	9.00
	B3	Ispra		1.52	5.54	8.57
		Karlsruhe	4.03	1.55	5.65	8.80
	B4	Ispra	4.22	1.57	5.24	8.35
	C5	Karlsruhe	4.36	1.78	5.12	8.42
	E3	Ispra	4.58	1.59	5.02	8.11
	E5	Ispra		1.78	4.73	8.28
		Karlsruhe	4.92	1.87	4.65	8.20
C16	A1 (1)	Ispra	3.80	1.46	3.77	6.10
	A1 (2)	Ispra	3.72	1.54	4.59	7.16
	B3	Ispra		1.05	4.84	6.65
		Karlsruhe	2.73	1.10	4.87	6.71
	C5	Karlsruhe	2.96	1.26	4.59	6.50
	E5	Ispra		1.10	4.31	6.58
		Karlsruhe	3.33	1.33	4.28	6.54

(a) The reported values have been corrected for:

^{148}Nd burn out by neutron capture,

^{148}Nd build up by ^{147}Nd (n,γ) ^{148}Nd reaction,

^{137}Cs decay during irradiation.

TABLE 9 - Isotopic Ratios of Fission Gases

(Karlsruhe Laboratory)

Fuel Assembly	Sample	KRYPTON			XENON			
		$^{83}/_{86}$	$^{84}/_{86}$	$^{84}/_{83}$	$^{131}/_{134}$	$^{132}/_{134}$	$^{136}/_{134}$	$^{132}/_{131}$
B 23	B3	0.245	0.588	2.400	0.303	0.698	1.424	2.304
	C5	0.239	0.594	2.485	0.307	0.714	1.443	2.326
	E5			2.639	0.294	0.711	1.510	2.418
C 16	B3	0.256	0.571	2.229	0.334	0.675	1.363	2.017
	C5	0.254	0.573	2.253	0.327	0.666	1.404	2.037
	E5	0.249	0.581	2.333	0.328	0.675	1.450	2.059

TABLE 10 - Alpha Activity Ratios of Pu, Am and Cm Isotopes

Fuel Assembly	Sample	Laboratory	BEFORE SEPARATION				AFTER SEPARATION	
			Date of measurement	$\frac{^{238}Pu + ^{241}Am}{^{239}Pu + ^{240}Pu}$	$\frac{^{244}Cm}{^{239}Pu + ^{240}Pu}$	$\frac{^{242}Cm}{^{239}Pu + ^{240}Pu}$	Date of measurem.	$\frac{^{238}Pu}{^{239}Pu + ^{240}Pu}$
B 23	A1 (1)	Ispra	24.04.77	3.01	0.97	0.11	11.05.77	2.08
	A1 (2)	Ispra	24.04.77	3.81	1.77	0.13	11.05.77	2.66
	B3	Ispra	19.11.75	2.67	0.87	0.83	25.11.75	2.08
		Karlsruhe	23.03.76	2.68	0.83	0.47	30.03.76	2.19
	B4	Ispra	11.11.76	2.99	0.92	0.18	20.10.76	2.38
	C5	Karlsruhe	23.03.76	2.86	1.06	0.51	30.03.76	2.30
	E3	Ispra	11.11.76	3.00	0.92	0.19	25.10.76	2.26
	E5	Ispra	28.11.75	3.04	1.53	0.94	26.11.75	2.47
		Karlsruhe	23.03.76	3.11	1.42	0.53	30.03.76	2.54
C 16	A1 (1)	Ispra	24.04.77	2.15	0.33	0.066	11.05.77	1.33
	A1 (2)	Ispra	24.04.77	2.39	0.51	0.078	11.05.77	1.51
	B3	Ispra	19.11.75	1.61	0.20	0.44	26.11.75	1.16
		Karlsruhe	06.04.76	1.65	0.22	0.25	05.05.76	1.16
	C5	Karlsruhe	06.04.76	1.69	0.26	0.25	05.05.76	1.24
	E5	Ispra	20.11.75	1.86	0.32	0.57	27.11.75	1.37
		Karlsruhe	06.04.76	1.91	0.39	0.30	05.05.76	1.40

TABLE 11 - Burn-up Values (MWD/MTU) obtained by Independent Experimental Techniques

Fuel Assembly	Sample	Laboratory	^{148}Nd	^{137}Cs destructive	^{137}Cs (d) non-destructive
B23	A1 (1)	Ispra (a)	25,730	30,120	24,670
	A1 (2)	Ispra (a)	27,400	23,830	27,750
	B3	Ispra		21,690	21,580
		Karlsruhe	21,240 (*)	22,100	
	B4	Ispra	22,250	22,400	22,890
	C5	Ispra (b)			18,820
		Karlsruhe	22,970 (*)	25,330	23,530
	E3	Ispra (c)			20,450
		Ispra (a)	23,510	22,130	23,870
	E5	Ispra		25,380	21,380
		Karlsruhe	25,190	25,900	
C16	A1 (1)	Ispra	20,300	21,120	20,250
	A1 (2)	Ispra (a)	19,850	24,230	
	B3	Ispra		15,220	14,880
		Karlsruhe	14,390 (*)	15,680	
	C5	Karlsruhe(a)	15,840 (*)	18,200	15,890
	E5	Ispra (a)		15,970	19,750
		Karlsruhe	17,490	19,240	

(a) A fission product diffusion has been detected at the cutting positions, by gamma scanning performed in LMA Laboratory.

(b) Cutting position at 440 mm from the bottom.

(c) Cutting position at 1750 mm from the bottom.

(d) LMA Laboratory of JRC Ispra Establishment.

(*) Calibration points for burn-up determination by ^{137}Cs non-destructive measurements.

TABLE 12 - Nuclear Data Used in the Determination of the Burn-Up Values

ENERGY RELEASE PER FISSION			
^{235}U	201.7 MeV	^{239}Pu	210.0 MeV
^{238}U	205.0 MeV	^{241}Pu	212.4 MeV
FISSION YIELDS OF ^{137}Cs			
^{235}U	6.23 %	^{239}Pu	6.69 %
^{238}U	6.28 %	^{241}Pu	6.60 %
FISSION YIELDS OF ^{148}Nd			
^{235}U	1.69 %	^{239}Pu	1.69 %
^{238}U	2.13 %	^{241}Pu	1.91 %

TABLE 13 - Isotopic Composition of U from Mass Spectrometry

(atom %)

Fuel Assembly	Sample	Laboratory	^{235}U	^{236}U	^{238}U
B 23	A1 (1)	Ispra	0.669	0.343	98.988
	A1 (2)	Ispra	0.719	0.345	98.936
	B3	Ispra	1.016	0.307	98.677
		Karlsruhe	1.035	0.308	98.657
	B4	Ispra	0.948	0.315	98.737
	C5	Karlsruhe	0.894	0.328	98.778
	E3	Ispra	0.903	0.327	98.770
	E5	Ispra	0.700	0.340	98.960
		Karlsruhe	0.717	0.348	98.935
C 16	A1 (1)	Ispra	0.905	0.319	98.775
	A1 (2)	Ispra	1.034	0.301	98.665
	B3	Ispra	1.353	0.252	98.395
		Karlsruhe	1.359	0.254	98.387
	C5	Karlsruhe	1.286	0.258	98.456
	E5	Ispra	1.072	0.280	98.648
		Karlsruhe	1.096	0.287	98.617

TABLE 14 - Isotopic Composition of Pu at the Reactor Shut-down

(atom %)

Fuel Assembly	Sample	Laboratory	^{236}Pu (x 10^{-6})	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
B 23	A1 (1)	Ispra	13.38	1.01	55.57	26.87	11.69	4.86
	A1 (2)	Ispra	18.60	1.25	55.39	25.04	13.16	5.16
	B3	Ispra	14.69	0.98	64.15	21.87	10.40	2.60
		Karlsruhe		1.01	63.74	22.03	10.55	2.67
	B4	Ispra		1.16	62.29	22.95	10.70	2.90
	C5	Karlsruhe		1.09	60.54	24.10	10.99	3.28
	E3	Ispra		1.09	61.49	23.49	10.83	3.10
	E5	Ispra	9.48	1.23	56.93	26.33	11.33	4.18
		Karlsruhe		1.25	56.53	26.46	11.48	4.28
C 16	A1 (1)	Ispra		0.64	61.28	24.80	10.24	3.04
	A1 (2)	Ispra		0.69	63.61	21.91	10.92	2.87
	B3	Ispra	5.92	0.53	72.03	17.83	8.27	1.34
		Karlsruhe		0.50	71.80	17.92	8.42	1.36
	C5	Karlsruhe		0.55	69.79	19.47	8.62	1.57
	E5	Ispra	6.64	0.65	65.11	22.51	9.35	2.38
		Karlsruhe		0.65	65.04	22.64	9.42	2.25

TABLE 15 - Build up and Depletion of U Isotopes

(atoms/100 initial heavy atoms)

Fuel Assembly	Sample	Laboratory	^{235}U Depletion	^{236}U Build up	^{238}U Depletion
B 23	A1 (1)	Ispra	1.923	0.329	1.828
	A1 (2)	Ispra	1.879	0.329	2.241
	B3	Ispra	1.577	0.297	1.808
		Karlsruhe	1.557	0.298	1.889
	B4	Ispra	1.656	0.302	1.839
	C5	Karlsruhe	1.695	0.318	1.924
	E3	Ispra	1.689	0.316	1.969
	E5	Ispra	1.886	0.328	1.992
		Karlsruhe	1.869	0.336	2.057
C 16	A1 (1)	Ispra	1.692	0.308	1.363
	A1 (2)	Ispra	1.569	0.291	1.523
	B3	Ispra	1.238	0.246	1.196
		Karlsruhe	1.230	0.248	1.249
	C5	Karlsruhe	1.305	0.252	1.289
	E5	Ispra	1.516	0.273	1.274
		Karlsruhe	1.492	0.279	1.346

TABLE 16 - Build up of Plutonium Isotopes (atoms per 1000 initial heavy atoms)

Fuel Assembly	Sample	Laboratory	^{236}Pu (x 10^{-7})	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu	TOTAL Pu
B 23	A1 (1)	Ispra	10.67	0.068	3.72	1.80	0.782	0.325	6.695
	A1 (2)	Ispra	15.61	0.108	4.78	2.15	1.128	0.442	8.608
	B3	Ispra	12.34	0.080	5.29	1.81	0.857	0.215	8.252
		Karlsruhe		0.086	5.41	1.87	0.884	0.224	8.474
	B4	Ispra		0.092	5.01	1.84	0.859	0.232	8.033
	C5	Karlsruhe		0.089	4.91	1.95	0.879	0.263	8.091
	E3	Ispra		0.084	4.80	1.83	0.844	0.242	7.800
	E5	Ispra	7.34	0.097	4.52	2.09	0.898	0.331	7.936
		Karlsruhe		0.099	4.45	2.08	0.892	0.333	7.854
C 16	A1 (1)	Ispra		0.036	3.62	1.46	0.604	0.179	5.899
	A1 (2)	Ispra		0.048	4.40	1.52	0.756	0.198	6.922
	B3	Ispra	3.77	0.033	4.66	1.15	0.536	0.087	6.466
		Karlsruhe		0.033	4.69	1.17	0.542	0.088	6.523
	C5	Karlsruhe		0.035	4.42	1.23	0.537	0.098	6.320
	E5	Ispra	4.16	0.041	4.15	1.43	0.596	0.151	6.368
		Karlsruhe		0.041	4.13	1.43	0.590	0.144	6.335

TABLE 17 - Build up of Cm and Am Isotopes

(atoms/10^6 initial heavy atoms)

Fuel Assembly	Sample	Laboratory	^{242}Cm	^{244}Cm	^{241}Am (x 10^{-2})
B 23	A1 (1)	Ispra	9.92	8.65	3.73
	A1 (2)	Ispra	14.32	19.28	6.55
	B3	Ispra	9.37	8.46	3.10
		Karlsruhe	9.22	8.36	
	B4	Ispra	9.17	9.16	
	C5	Karlsruhe	9.90	10.58	1.04
	E3	Ispra	9.46	8.95	2.19
	E5	Ispra	11.29	15.24	2.12
		Karlsruhe	10.26	14.14	1.14
C 16	A1 (1)	Ispra	5.17	2.55	2.77
	A1 (2)	Ispra	6.76	4.37	2.64
	B3	Ispra	3.68	1.44	1.00
		Karlsruhe	3.80	1.62	0.94
	C5	Karlsruhe	3.76	1.89	0.32
	E5	Ispra	5.09	2.46	1.43
		Karlsruhe	4.82	2.99	1.02

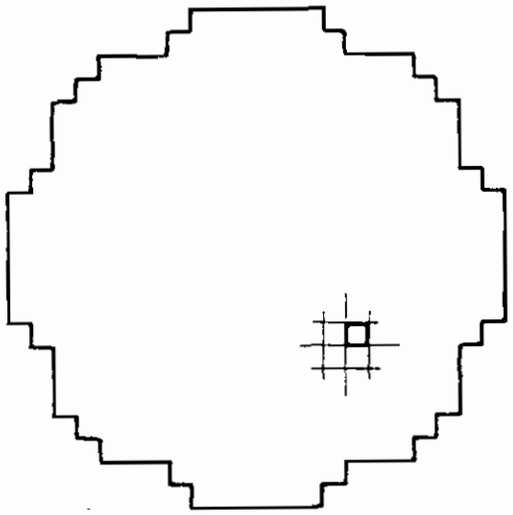
TABLE 18 - Average Differences Between the Measurements Performed in Ispra and Karlsruhe Laboratories on Pairs of Adjacent Pellets

ISOTOPIC RATIOS OF U AND Pu	
$^{235}U/^{238}U$	1.8 %
$^{236}U/^{238}U$	1.47 %
$^{240}Pu/^{239}Pu$	0.3 %
$^{239}Pu/^{238}U$	0.05 %
Total Pu/U	0.5 %

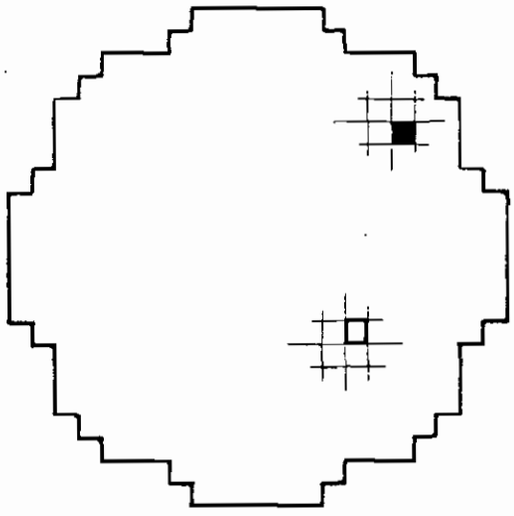
ISOTOPIC COMPOSITION OF U AND Pu			
^{235}U	1.75 %	^{239}Pu	0.45 %
^{236}U	1.5 %	^{240}Pu	0.55 %
^{238}U	0.02 %	^{241}Pu	1.3 %
^{238}Pu	0.45 %	^{242}Pu	2.95 %

BUILD UP AND DEPLETION OF U					
^{235}U	1.1 %	^{236}U	1.45 %	^{238}U	4.45 %
BUILD UP OF Pu, Cm AND Am					
^{238}Pu	1.2 %	^{241}Pu	0.7 %	^{242}Cm	3.2 %
^{239}Pu	0.2 %	^{242}Pu	0.2 %	^{244}Cm	6.4 %
^{240}Pu	1.15 %	Total Pu	0.45 %	^{241}Am	10.1 %

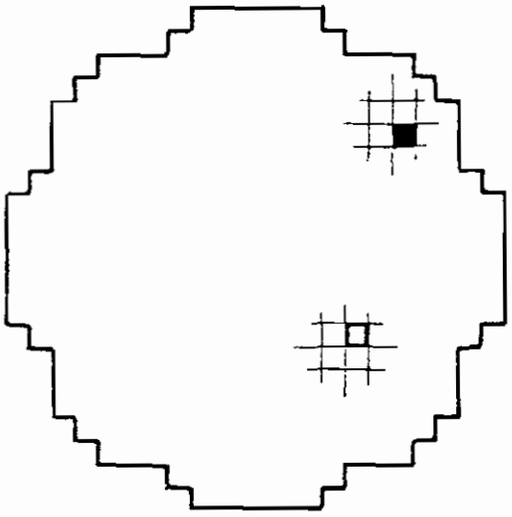
SECOND IRRADIATION CYCLE



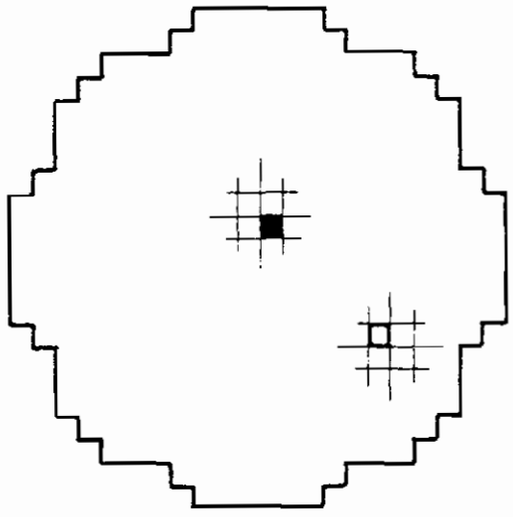
THIRD IRRADIATION CYCLE



FOURTH IRRADIATION CYCLE



FIFTH IRRADIATION CYCLE



□ FUEL ELEMENT B23 - Positions H-4 and J-4

■ FUEL ELEMENT C16 - Positions J-9 and F-7

FIG. 1 : SCHEMATIC CORE MAPS OF THE GUNDREMMINGEN REACTOR
DURING DIFFERENT IRRADIATION CYCLES
THE POSITION OF THE ELEMENTS B23 AND C16 ARE INDICATED

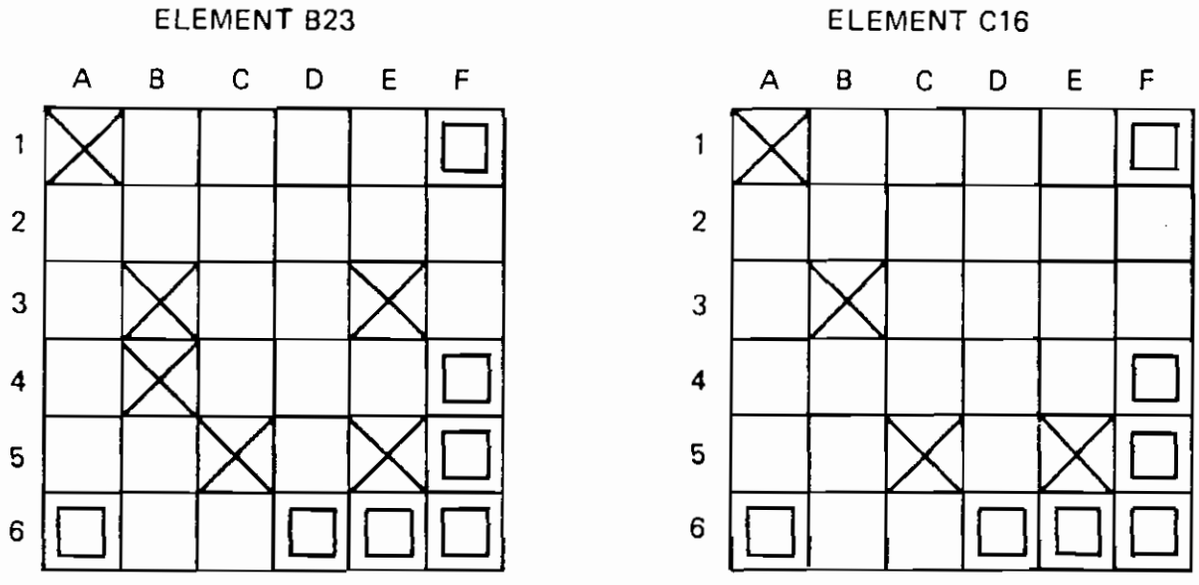


FIG. 2 : LOCATION OF THE FUEL RODS OF ELEMENTS B23 AND C16 SELECTED FOR ANALYSES

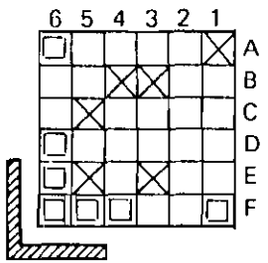
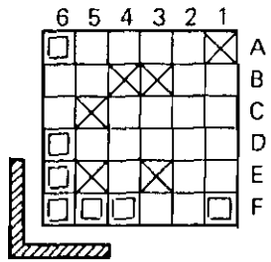
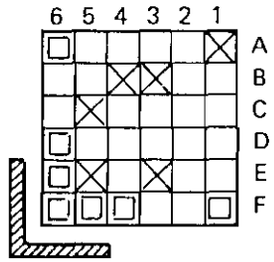
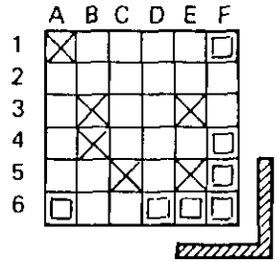
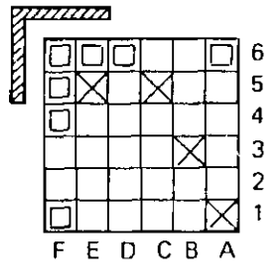
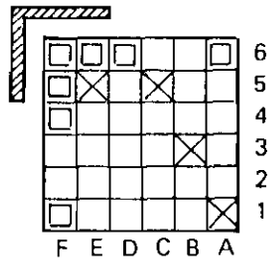
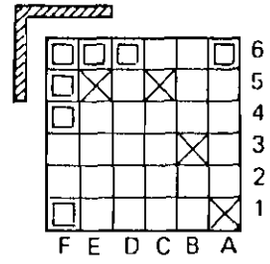
FUEL ELEMENT	IRRADIATION CYCLES			
	SECOND	THIRD	FOURTH	FIFTH
B 23	 Position H 4	 Position H 4	 Position H 4	 Position J 4
C 16		 Position J 9	 Position J 9	 Position E 7

FIG. 3 : SCHEMATIC POSITIONS OF ELEMENTS B23 AND C16 IN RESPECT TO THE CONTROL ROD DURING DIFFERENT IRRADIATION CYCLES

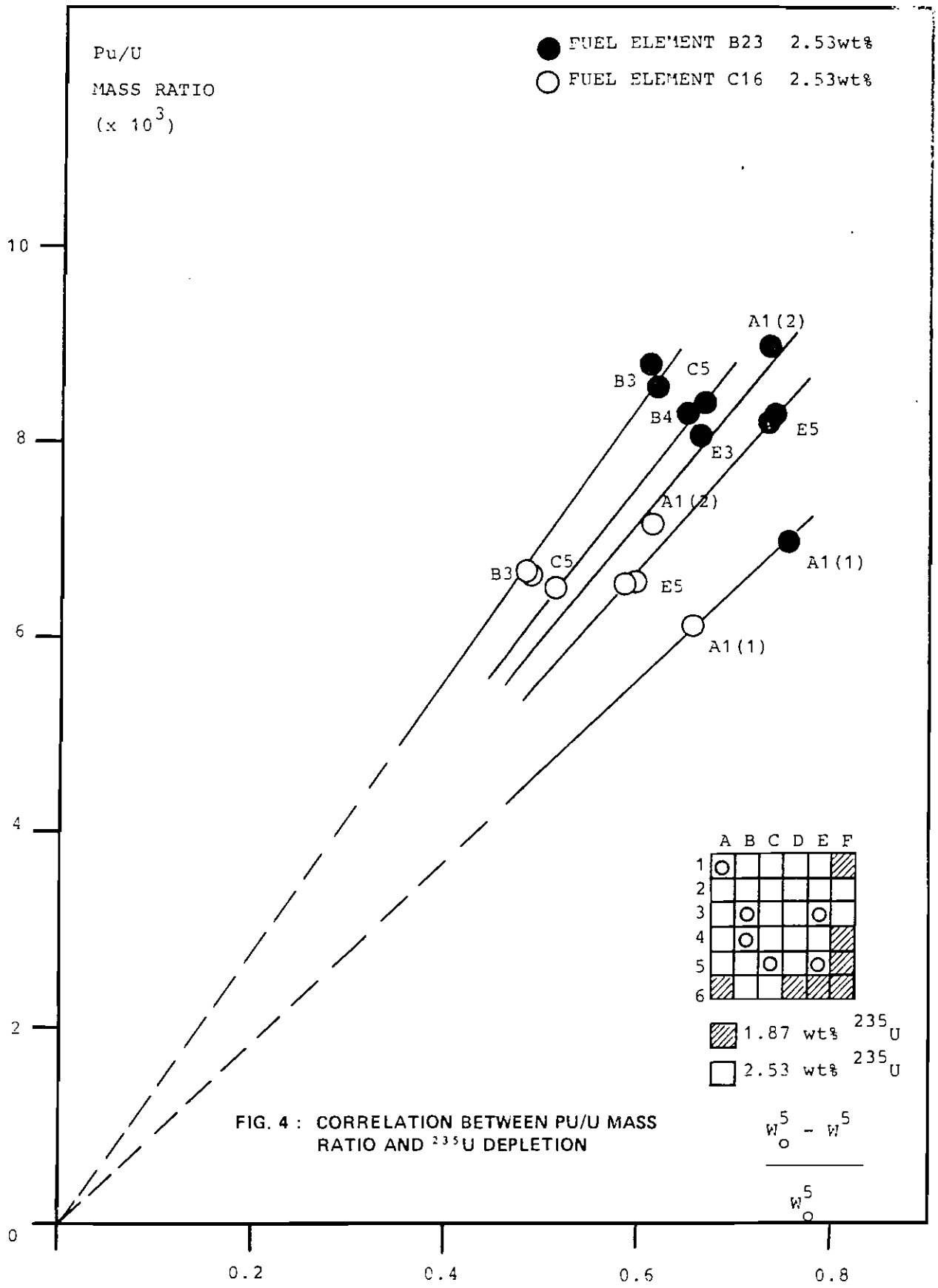
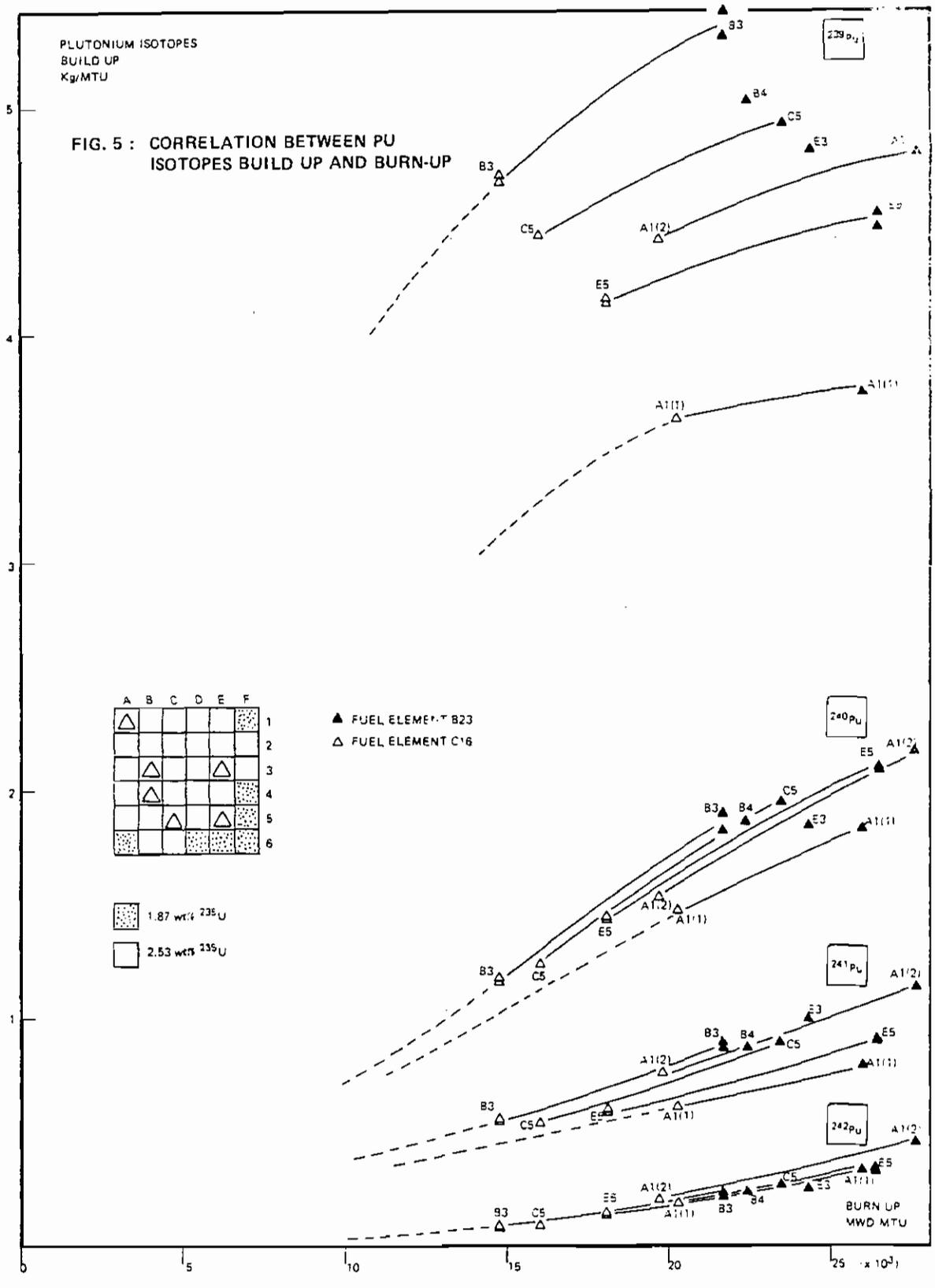


FIG. 4 : CORRELATION BETWEEN PU/U MASS RATIO AND ^{235}U DEPLETION


PLUTONIUM ISOTOPES
BUILD UP
Kg/MTU
FIG. 5 : CORRELATION BETWEEN PU ISOTOPES BUILD UP AND BURN-UP
A B C D E F
1
2
3
4
5
6
1.87 wt% 235U
2.53 wt% 235U
▲ FUEL ELEMENT B23
△ FUEL ELEMENT C16
239Pu
240Pu
241Pu
242Pu
B3
B4
C5
E3
E5
A1(2)
A1(1)
BURN UP
MWD MTU
0
5
10
15
20
25
x 10³
1
2
3
4
5

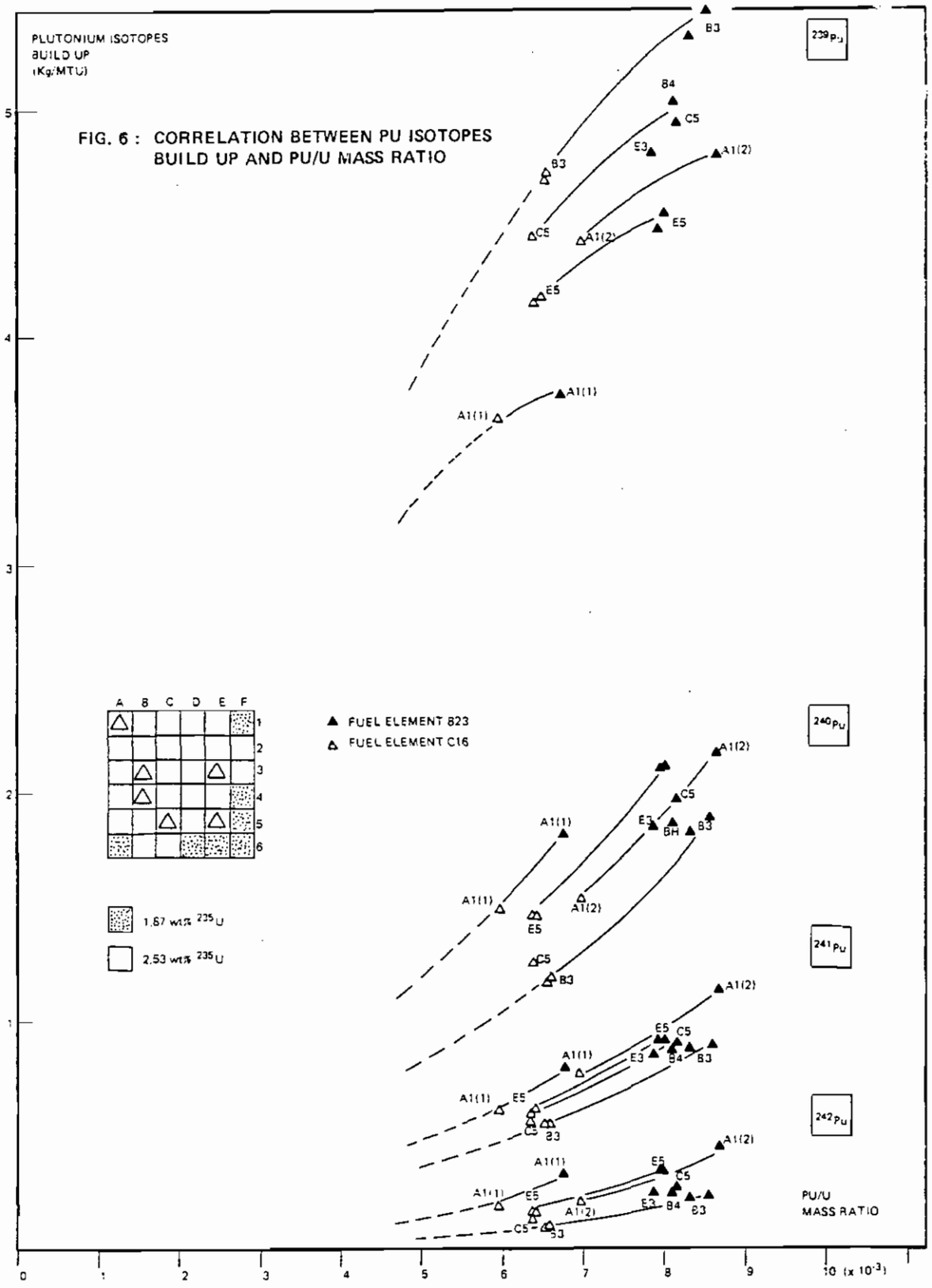


FIG. 6 : CORRELATION BETWEEN PU ISOTOPES BUILD UP AND PU/U MASS RATIO

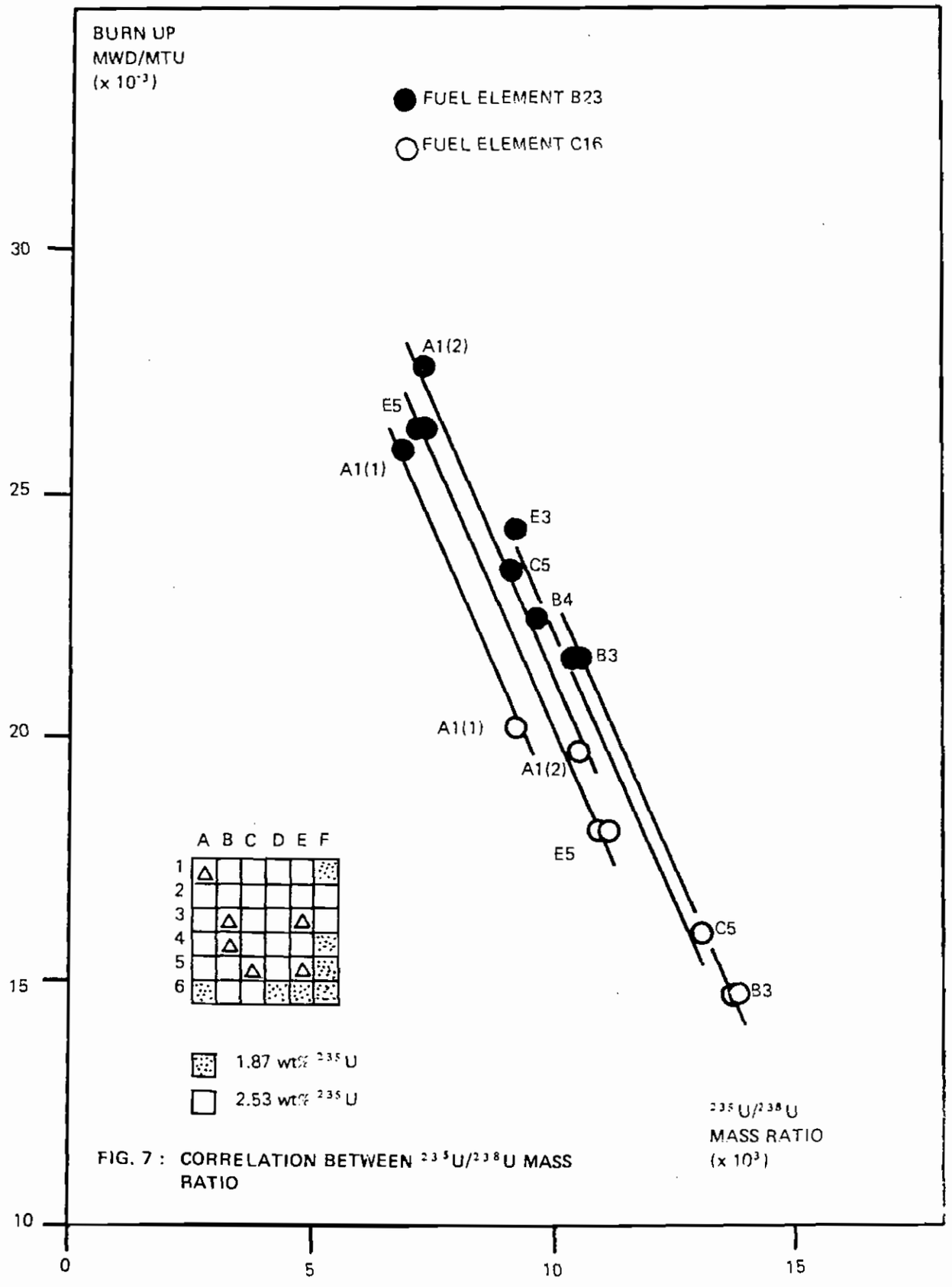


FIG. 7 : CORRELATION BETWEEN $^{235}U/^{238}U$ MASS RATIO

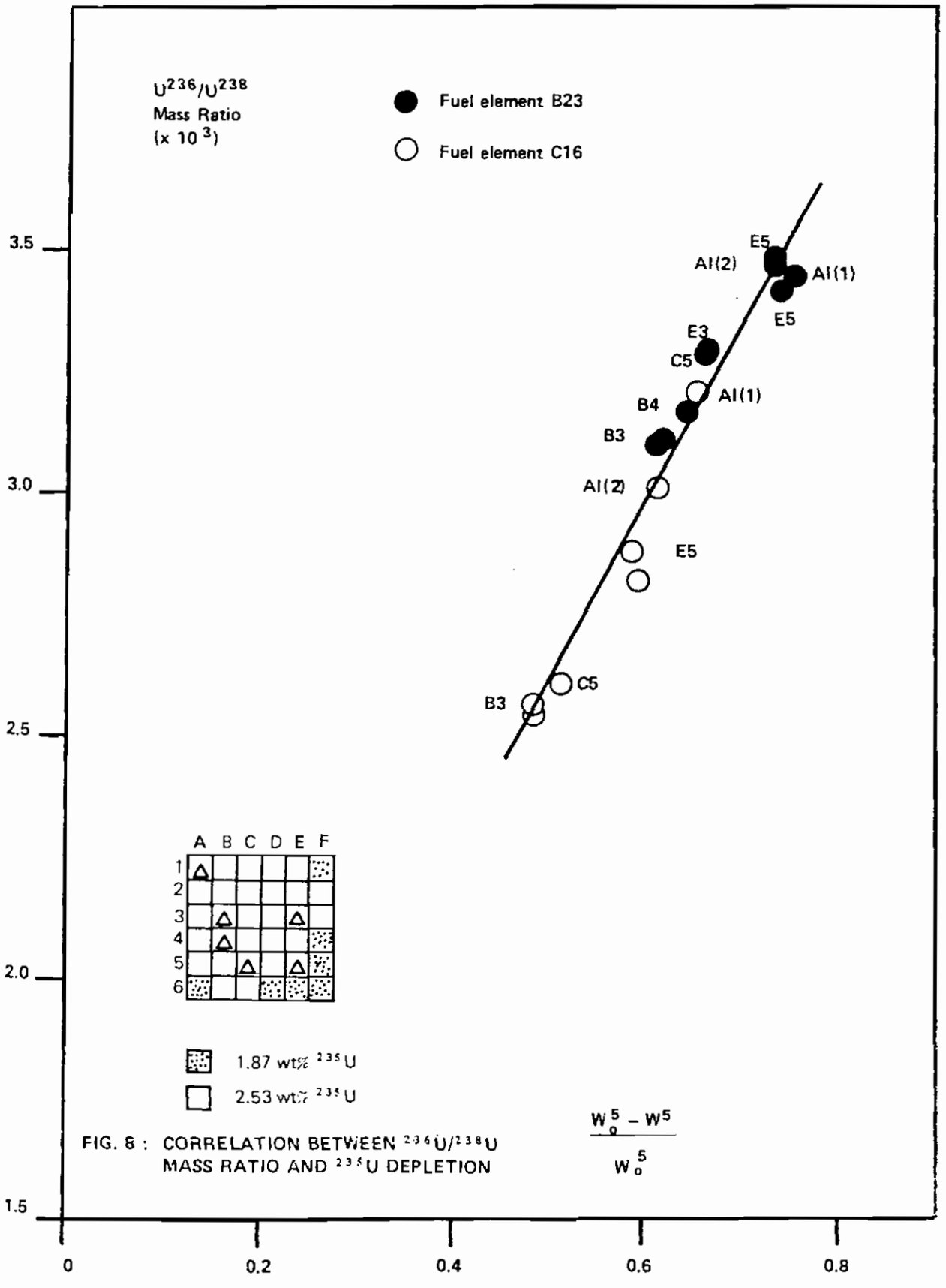


FIG. 8 : CORRELATION BETWEEN $^{236}U/^{238}U$ MASS RATIO AND ^{235}U DEPLETION

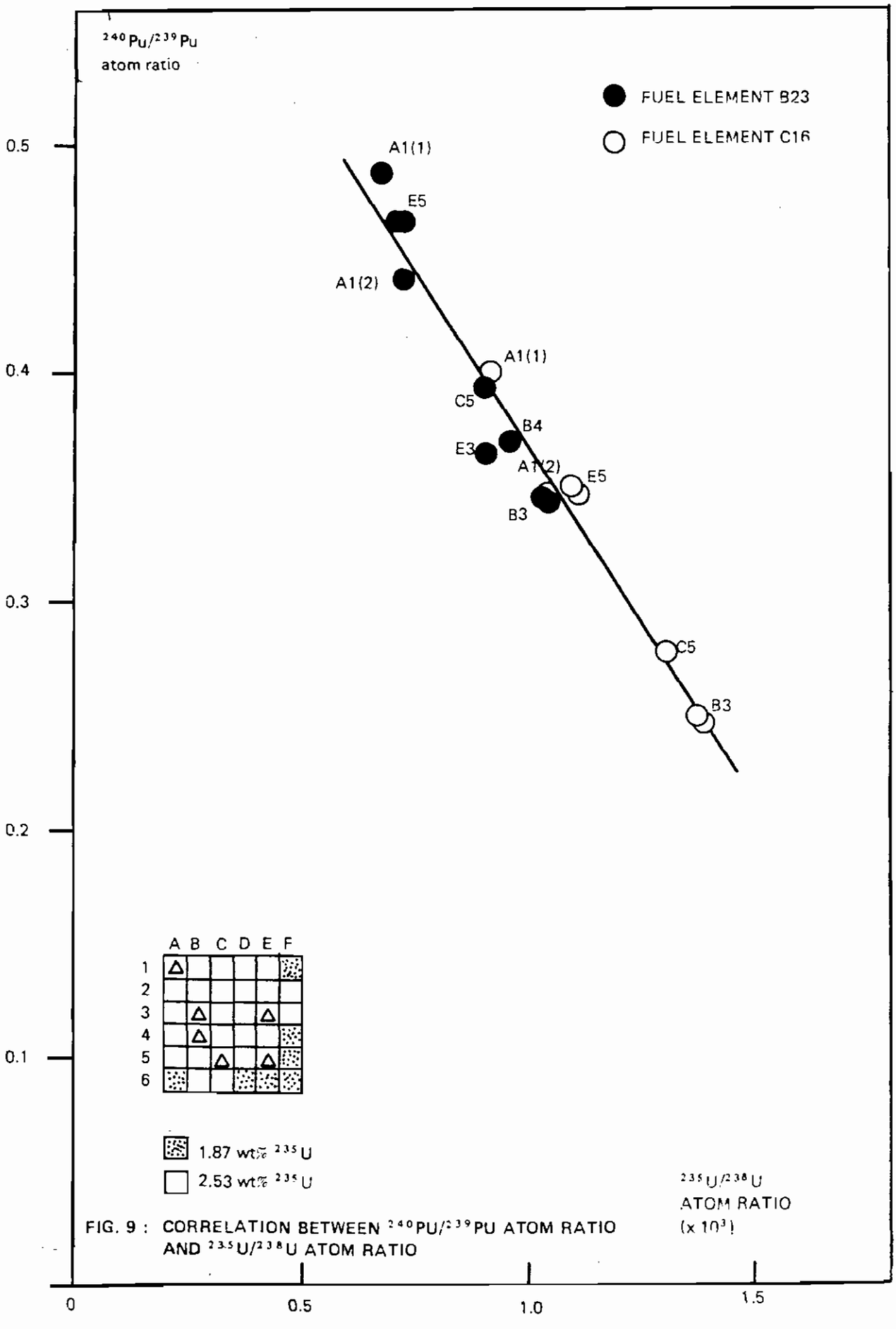


FIG. 9 : CORRELATION BETWEEN $^{240}PU/^{239}PU$ ATOM RATIO AND $^{235}U/^{238}U$ ATOM RATIO

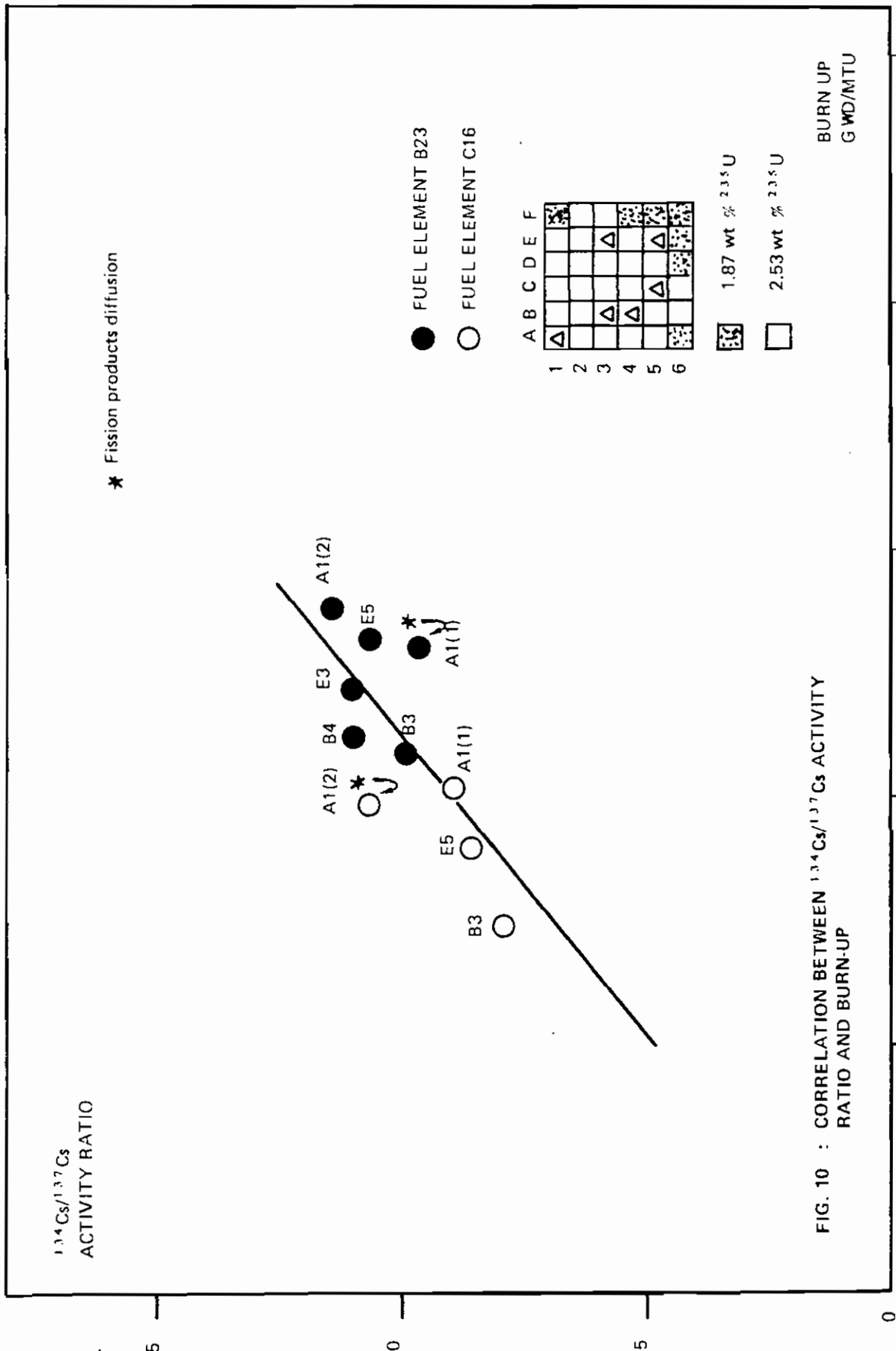


FIG. 10 : CORRELATION BETWEEN $^{134}Cs/^{137}Cs$ ACTIVITY RATIO AND BURN-UP

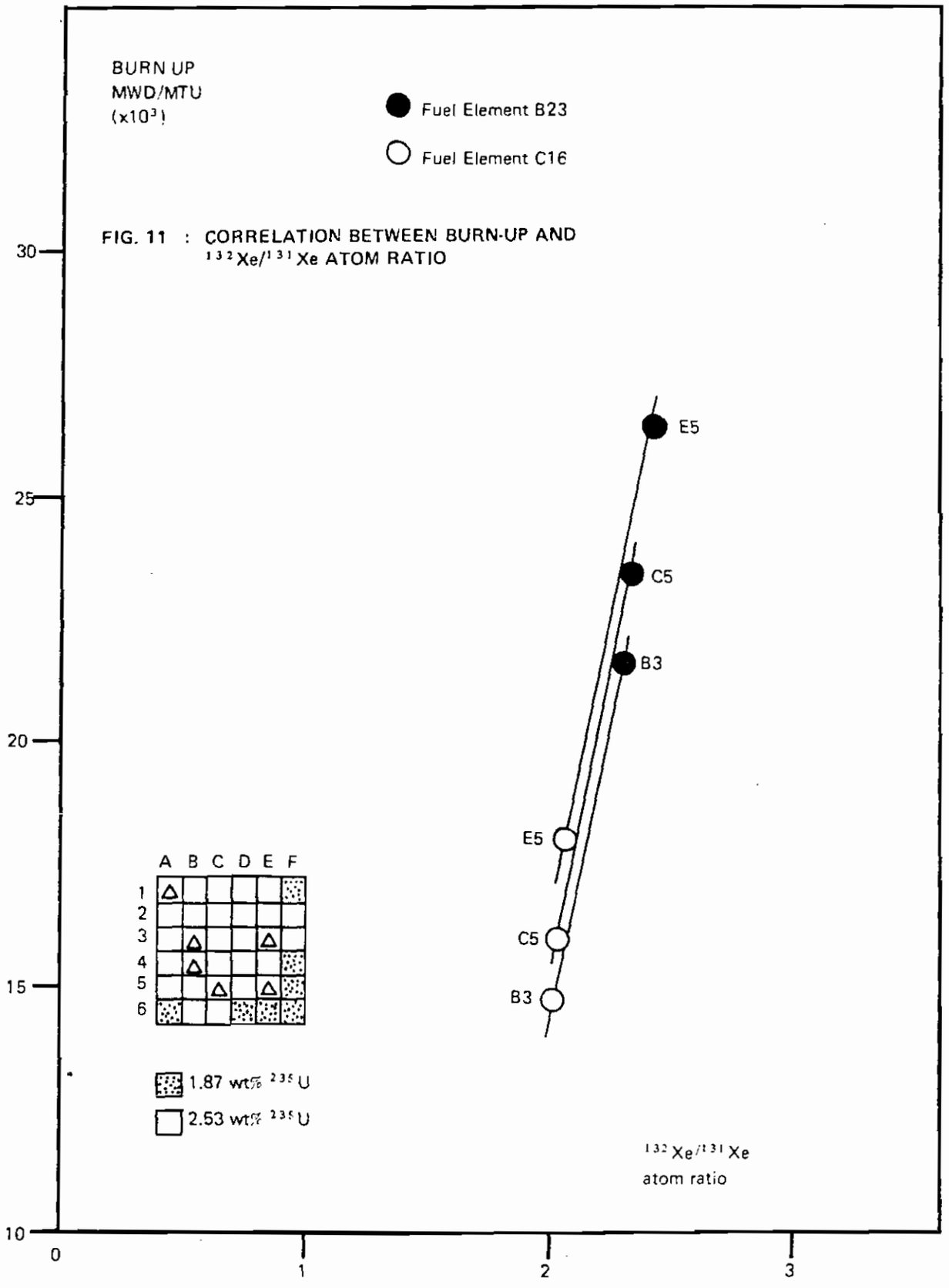


FIG. 11 : CORRELATION BETWEEN BURN-UP AND $^{132}Xe/^{131}Xe$ ATOM RATIO

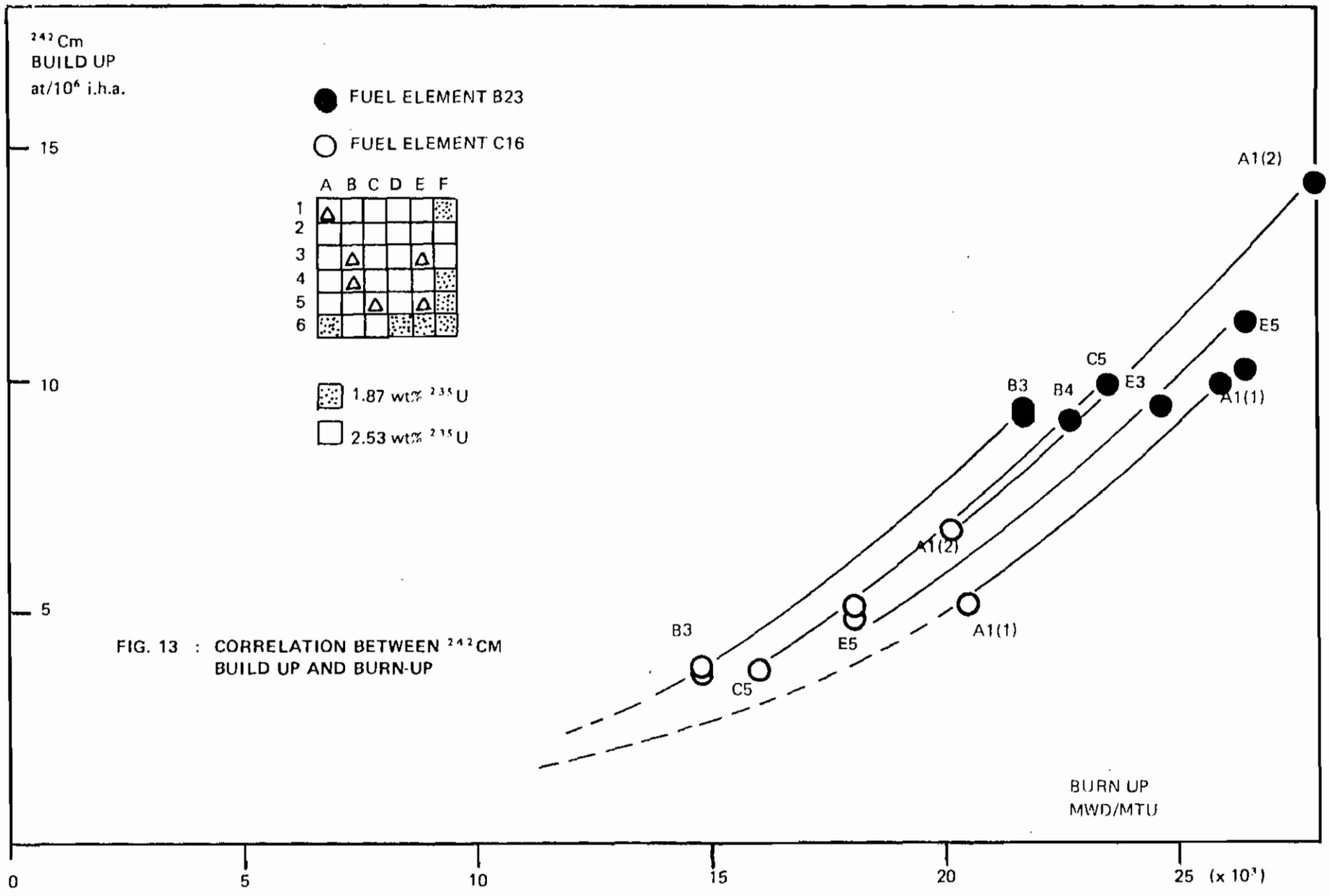


FIG. 13 : CORRELATION BETWEEN ^{242}CM BUILD UP AND BURN-UP

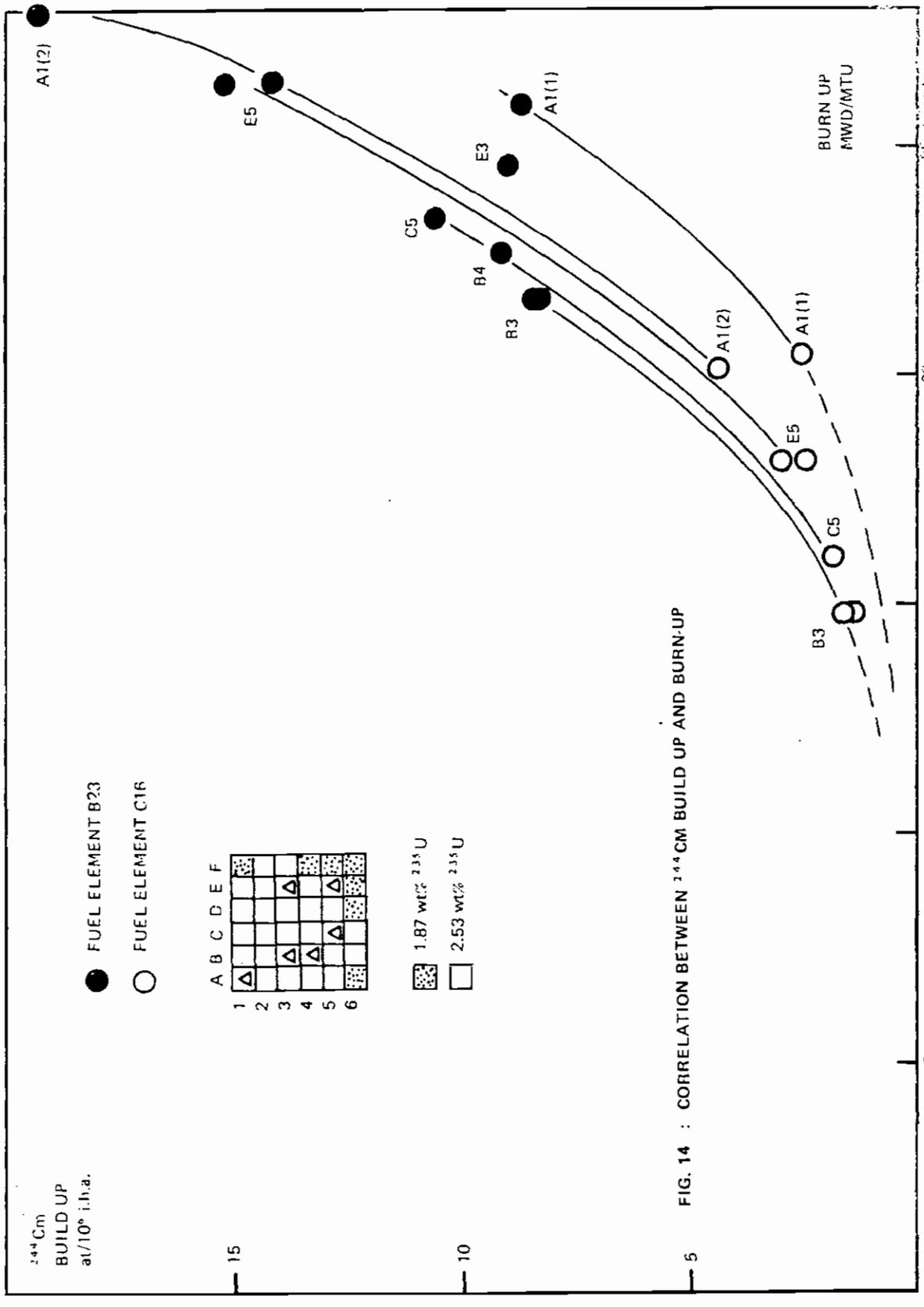


FIG. 14 : CORRELATION BETWEEN ^{244}CM BUILD UP AND BURN-UP