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ABSTRACT

Concern for nuclear proliferation is likely to preclude future supply of highly enriched uranium fuel for research reactors such as the University Training Reactor Moata. This study calculates the fuel densities necessary to maintain the reactivity per plate of the present high enrichment (90 per cent ^{235}U) fuel for a range of lower enrichments assuming that no geometry changes are allowed.

The maximum uranium density for commercially available aluminium-type research reactor fuels is generally considered to be about 1.7 g cm^{-3}. With this density limitation, the minimum enrichment to maintain present reactivity per plate is about 35 per cent ^{235}U. For low enrichment (max. 20 per cent ^{235}U) fuel, the required U density is about 2.9 g cm^{-3}, which is beyond the expected range for UAl_x-Al but within that projected for the longer term development and full qualification for U_3O_8-Al. Medium enrichment (nominally

(Continued)

45 per cent ^{235}U) UAl_x-Al would be entirely satisfactory as an immediate replacement fuel, requiring no modifications to the reactor and operating procedures, and minimal reappraisal of safety issues.

Included in this study are calculations of the fuel coefficients at various enrichments, the effect of replacing standard fuel plates or complete elements with 45 per cent enriched fuel, and the reactivity to be gained by replacing 12-plate with 13-plate elements.

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DENSITY; FUEL PLATES; HIGHLY ENRICHED URANIUM; MOATA REACTOR; MODERATELY ENRICHED URANIUM; REACTIVITY; SOLID FUELS

CONTENTS

(Continued)

1. INTRODUCTION

The Moata reactor has been operated at Lucas Heights for some 20 years, initially with a maximum power of 10 kW but upgraded to 100 kW in 1972. For flexibility with safety, the excess reactivity of the system has been kept to a minimum, but burn-up has now reached the stage where it is necessary to add fuel. The 12 fuel elements (Figure 1) are currently built up to a maximum of 12 plates each, except that in one core position, 11 fuel plates and 1 dummy (aluminium) plate are used, and in another position, 10 fuel plates and two dummies are used. Initially these dummy plates will be replaced with fuel plates, but subsequent increases in core fuel content will be made by substituting 13-plate for 12-plate elements.

To increase the core loading, as insurance against fuel plate damage and to ensure future requirements, new fuel is required. From the operational point of view, it would be most satisfactory to use additional or replacement fuel similar in all respects to that in current use. This would ensure that the only difference experienced would be due to small manufacturing tolerances.

Concern with nuclear proliferation, however, means that there is now considerable resistance to the supply of highly enriched uranium (HEU) to research reactors, and it is most unlikely that 90 per cent enriched fuel will be available for future Moata fuel supplies.

This paper examines the possibility of using lower enrichments and calculates the various fuel coefficients and their spatial variations.

2. MOATA AND ITS FUEL

The University Training Reactor (UTR) Moata (Figure 1) was designed and built by the Advanced Technology Laboratories, USA, and first went critical in April 1961. It is a thermal heterogeneous reactor fuelled with UAl_x-Al alloy clad in aluminium (Figure 2). The twelve fuel elements are cooled and moderated by light water and reflected by graphite (horizontally) and water (vertically).

The design is based on the Argonaut reactor developed at the Argonne National Laboratory, USA, the main difference being the two slab cores of the

UTR and the annular core of the Argonaut. Table 1 gives details of the fuel elements, plates and core tanks of Moata.

3. CALCULATIONAL METHOD

All calculations were made using AUS, the Australian modular scheme for reactor neutronics calculations [Robinson 1975], which is a method of dynamically linking the required module or set of modules. The modules used are MIRANDA, EDIT, ICPP, POW3D.

The MIRANDA module [Robinson 1977] is used for cross-section preparation. It includes a multi-region resonance calculation and a cell-averaged flux solution for preliminary group condensation. The 128-group cross-section library is an AUS data pool, AUS.ENDFB, based on the ENDFB/IV cross-section library [Honeck 1964].

The EDIT module provides editing and flux group condensing facilities. ICPP [based on the work of Doherty 1969a-c, 1970] calculates many group, few region fluxes within a cell using first collision probability routines. POW [Pollard 1974] and POW3D [AAEC/E report, in preparation] are general purpose diffusion codes. POW and POW3D can be used in the two-dimensional mode, but POW3D is much faster in operation.

The models used in the calculation are shown in Figures 3 to 5. Details of the fuel mixtures are given in Table 2.

4. METHODS AND RESULTS

4.1 Most Appropriate Replacement Fuel

A calculation is made first with a complete core fuelled with 90 per cent enriched uranium as an aluminium alloy clad in aluminium. The calculated effective multiplication coefficient k_{eff} is used as the datum for all other calculations.

A set of three calculations at different uranium densities is then made at each enrichment and the results (Figure 6) are fitted to the equation

$$k_{eff} = k_o + Am + Bm^2 \qquad (1)$$

where m is the mass of ^{235}U in the reactor core. This equation is then used to determine the core ^{235}U mass or uranium density necessary to produce a core of the same reactivity as the standard versions (Figure 7 and Table 2). Although, in the long-term, uranium densities in UAl_x fuel are expected to reach about 2.8 g cm^{-3}, the present fully proved maximum is 1.7 g cm^{-3} [IAEA 1980], which will allow enrichments down to about 35 per cent to be used.

Differentiation of Equation 1 results in the mean core fuel coefficient

$$C_{fuel} = \frac{\delta k}{\delta m} = A + 2Bm \qquad (2)$$

defined as the change in reactivity produced by an increase of 1 gram of ^{235}U in the reactor core; the values are listed in Table 2. The variation in mean core fuel coefficient with density or enrichment is shown in Figure 8.

4.2 The Addition of Standard Fuel to a Vacant Plate Position in a 12-plate Element

To ensure a proper coolant flow, 11-plate elements have the missing fuel plate substituted by an aluminium dummy plate of the same dimensions. To calculate the effect of replacing a dummy plate with a fuel plate, the mesh regions of the calculation are made to coincide with the fuel plates and the surrounding coolant. The material in each region is then defined as a fuel and coolant mixture or an aluminium and coolant mixture. Because the model is a quadrant of the core reflected on two boundaries, the calculated reactivity difference is that due to the replacement of four plates, i.e. one each in each of the four symmetrically positioned elements.

These results also give the fuel coefficient of reactivity, i.e. the reactivity change due to the addition of a whole fuel plate.

The effect of fuel/dummy substitution is calculated for the two outer plate positions (which would be the normal substitution positions) and for a central plate in each of the three different element positions in the core quadrant. The fuel plate positions are shown in Figure 9 and the results given in Table 3.

Replacing dummy plates with 45 per cent enriched fuel plates could result in slightly different reactivity changes - see, for example, the changes produced when substituting whole elements (Table 4). These differences, however, would be much smaller than those caused by variation in fuel content due to manufacturing tolerances. For the latter, the standard deviation is ± 1.34 g which is worth about ± 11.5 x 10^{-5} in reactivity.

4.3 The 13-plate Element with Standard 90 per cent Enriched Fuel

In this method, interplate separation is reduced and the calculation described in Section 4.1 is then carried out with the standard fuel atomic number densities. This gives the reactivity for the twelve 13-plate elements, and the reactivity change due to each of the three different 13-plate element positions can be determined by weighting with the fuel coefficients reported in Section 4.2. The mean gain in reactivity obtained by replacing one 12-plate element with a 13-plate element of 90 per cent enriched fuel is 229.4 x 10^{-5}.

4.4 The Substitution of 45 per cent Enriched Plates for 90 per cent Enriched Plates in 12-plate Elements

This calculation is carried out in two parts: first, a 45 per cent enriched fuel is calculated as shown in Section 4.1, the the resulting cross sections being stored on a library tape. A second calculation is then made for a core of 90 per cent enriched fuel in which mesh regions coinciding with specified fuel plates have been filled with material detailed from the 45 per cent fuel library tape. This gives a reactivity change due to the substitution of four equivalent plates. The results are given in Table 3, the magnitude being of the same order as that due to variations in the fuel contents of the plates.

4.5 The Substitution of 12-plate 45 per cent Enriched Elements for 12-plate 90 per cent Enriched Elements

This calculation is carried out in case there is some physical or administrative reason for not mixing the enrichment within an element. The method is similar to that decribed in Section 4.4 except that a whole element is substituted. The results are given in Table 4; the variation is less than that due to variation in the total weight of ^{235}U in the elements.

5. CONCLUSIONS

To avoid the cost and inconvenience of modifying Moata, the constraint of current established fuel technology (max. U density ∿ 1.7 g cm^{-3}) necessitates the use of fuel of minimum enrichment ∿ 35 per cent ^{235}U.

If fuel of the standard medium enrichment of 45 per cent ^{235}U is used, there appear to be no reactivity-related problems and the fuel can be substituted on a plate for plate or element for element basis. Although there are some spatial reactivity effects, these are not larger than the variations due to the manufacturing tolerances in the fuel content of the plates and will not be noticed in practice.

Projected uranium density limits for UAl_x-Al and U_3O_8-Al development programs (Figure 7) suggest that only with the latter may it be subsequently possible to change to low enrichment ($\leq$ 20 per cent ^{235}U) on a similar equivalent reactivity basis. The required U density would be about 2.9 g cm^{-3}.

6. ACKNOWLEDGEMENTS

It is a pleasure to record the instruction in the manipulation of the various codes given by Dr J Pollard and Mr G Robinson - without their assistance this report would not have been written.

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TABLE 1
ELEMENT AND TANK DIMENSION

Coolant moderator	Demineralised H_2O
Core containment	Two aluminium tanks:
	Height 1470 mm
	Length 506 mm
	Width 148 mm
	Wall 6.35 mm
Fuel elements	Parallel plate
Total number	12 (6 in each tank)
Fuel plates/element	Normally 12
Overall fuel plate dimensions	660 x 76.2 x 2.03 mm
Fuel alloy dimensions	584.2 x 69.85 x 1.016 mm
Alloy composition	90% enriched U as 18.6 wt % alloy (22 g U5/plate)
Cladding	Aluminium, 0.508 mm thick
*Interplate coolant gap	10.16 mm (12 plate element)
Reflectors	Water above and below core tanks, graphite on sides.

*For the 13-plate elements the overall size of the element is unchanged but the plate separation is reduced to 9.144 mm to accommodate the 13 plates.

TABLE 2
FUEL DETAILS FOR CRITICAL CORES

Enrichment %	^{235}U per Plate g	Element Densities g cm^{-3}			Atomic Number Densities x 10^{24}			Fuel Coefficient x 10^{-5} g^{-1} ^{235}U
		^{235}U	^{238}U	Total U	^{235}U	^{238}U	Al	
10	26.47	0.6385	5.7455	6.384	0.001636	0.01454	0.03994	6.451
20	24.20	0.5837	2.3353	2.919	0.001496	0.005909	0.05095	7.742
30	23.48	0.5663	1.3217	1.888	0.001451	0.003343	0.05423	8.179
45	22.90	0.5524	0.6746	1.227	0.001416	0.001709	0.05633	8.584
60	22.50	0.5427	0.3413	0.884	0.001392	0.0009163	0.05734	8.879
75	22.24	0.5364	0.1796	0.716	0.001375	0.0004526	0.05796	9.128
90	22.00	0.5306	0.0596	0.590	0.001360	0.0001490	0.05835	9.405

TABLE 3
REACTIVITY CHANGES WHEN REPLACING FUEL PLATES

Plate Position (Figure 9)	Δk per Plate x 10^{-5}	
	Replacing Dummy* With Standard Fuel	Replacing Standard Fuel* With 45% Enriched Fuel*
A	386.3	2.78
B	298.5	2.06
C	175.0	1.16
D	382.7	-2.59
E	289.3	-2.14
F	161.0	-0.92
G	321.8	2.06
H	244.7	1.43
I	143.3	0.58

The standard fuel is enriched to 90% ^{235}U and contains 22.0 g of ^{235}U per plate. The 45% enriched fuel contains 22.9 g ^{235}U per plate.

TABLE 4

THE VARIATION IN REACTIVITY WHEN SUBSTITUTING A 45 PER CENT ENRICHED FUEL ELEMENT CONTAINING 22.9 g OF ^{235}U FOR A 90 PER CENT ENRICHED FUEL ELEMENT CONTAINING 22.0 g OF ^{235}U

Fuel Element Position (Figure 5)	Change in Reactivity for 1 Element
1	-3.5×10^{-5}
2	-0.9×10^{-5}
3	$+4.4 \times 10^{-5}$

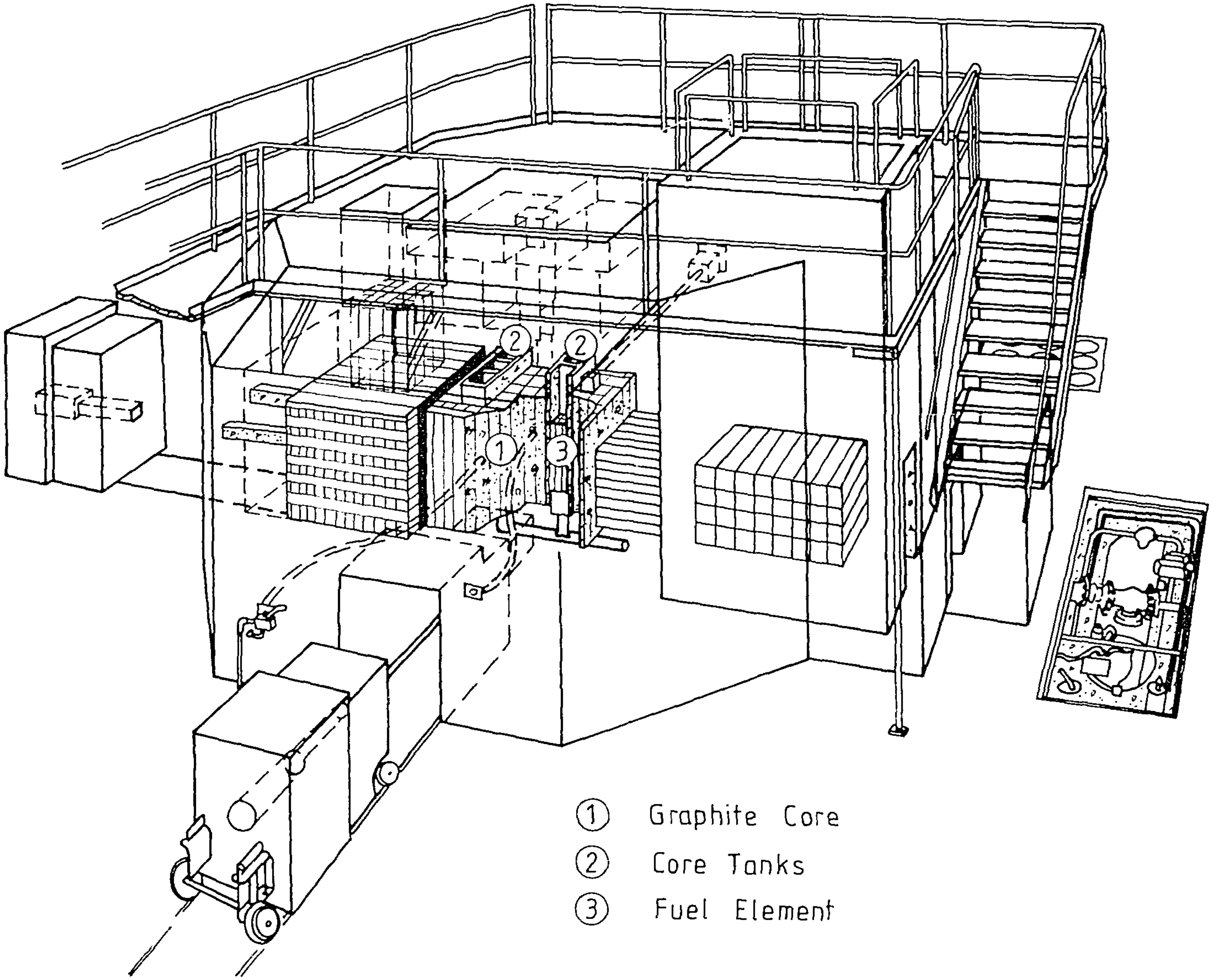

FIGURE 1. MOATA RESEARCH REACTOR

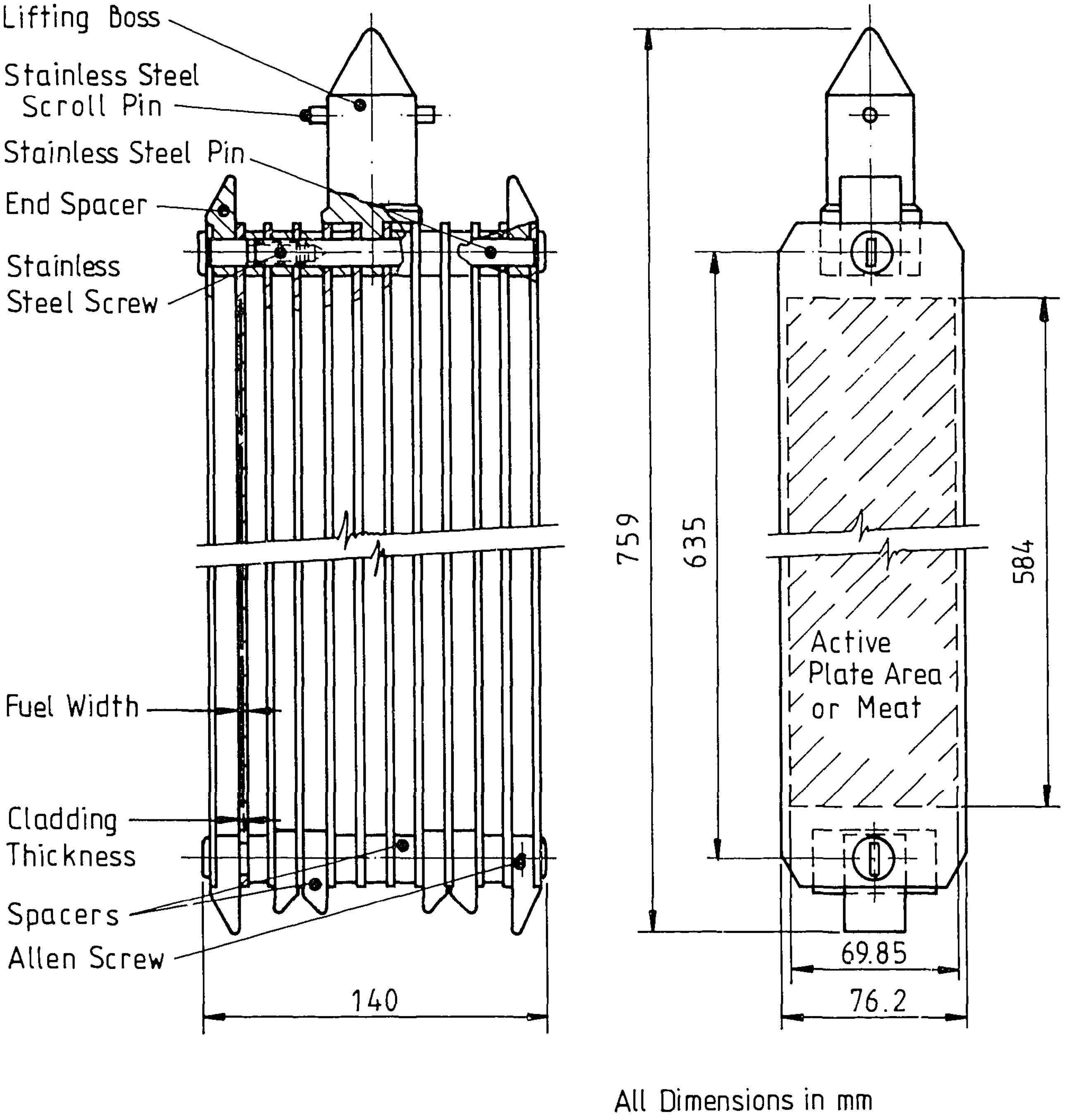

FIGURE 2. MOATA FUEL ELEMENT

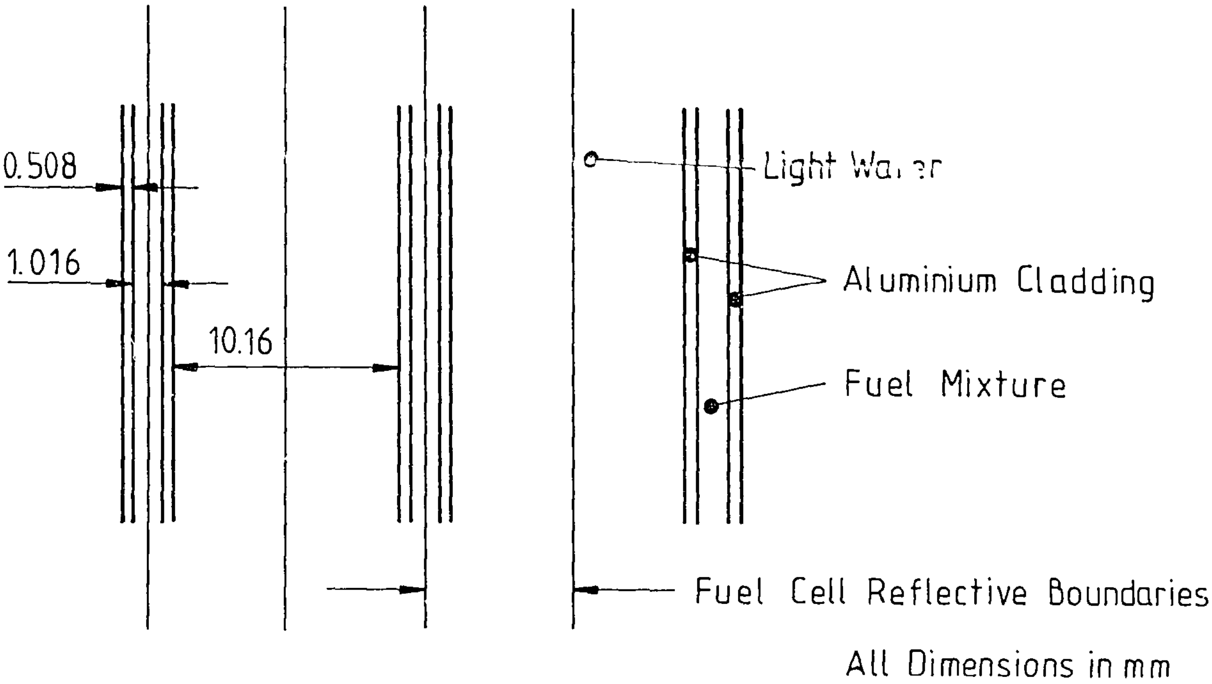

FIGURE 3. FUEL CELL I, INDIVIDUAL PLATES AND COOLANT CHANNELS

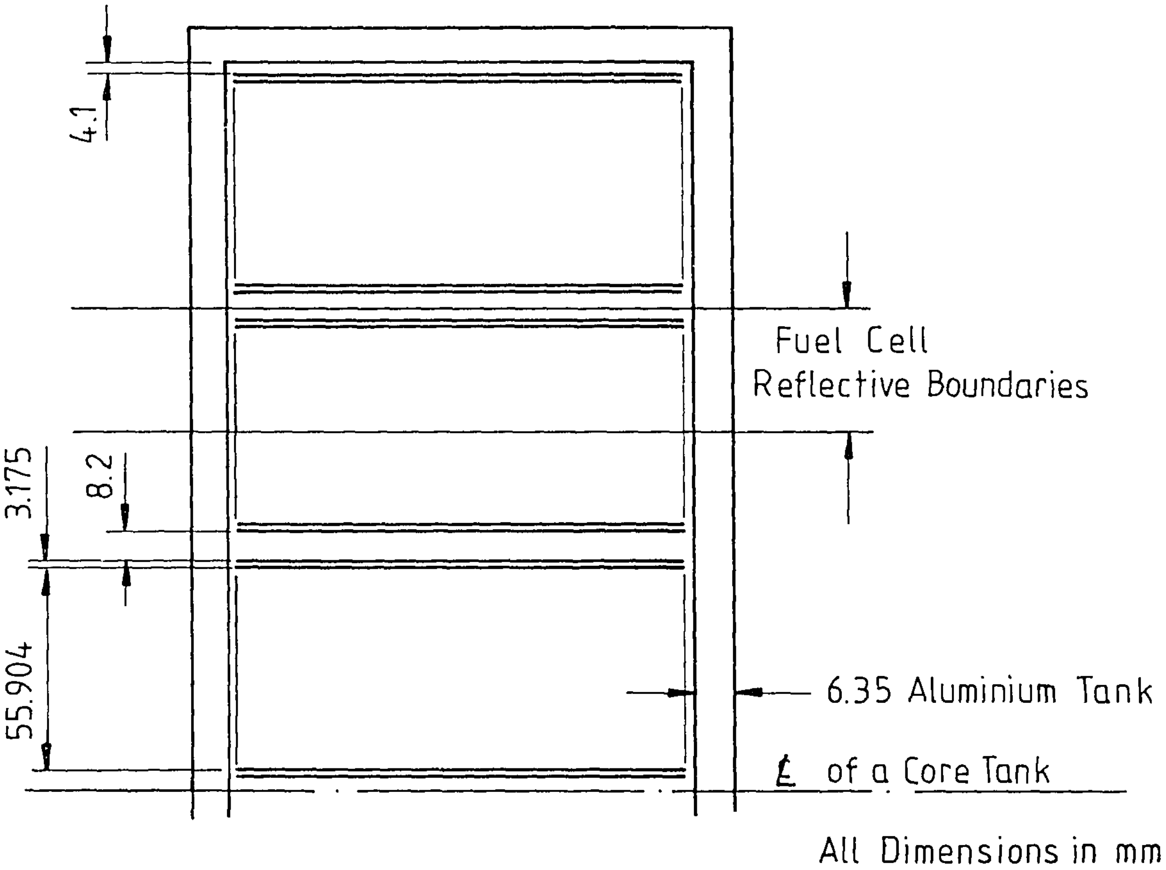

FIGURE 4. FUEL CELL II, VARIATION FROM ELEMENT TO ELEMENT

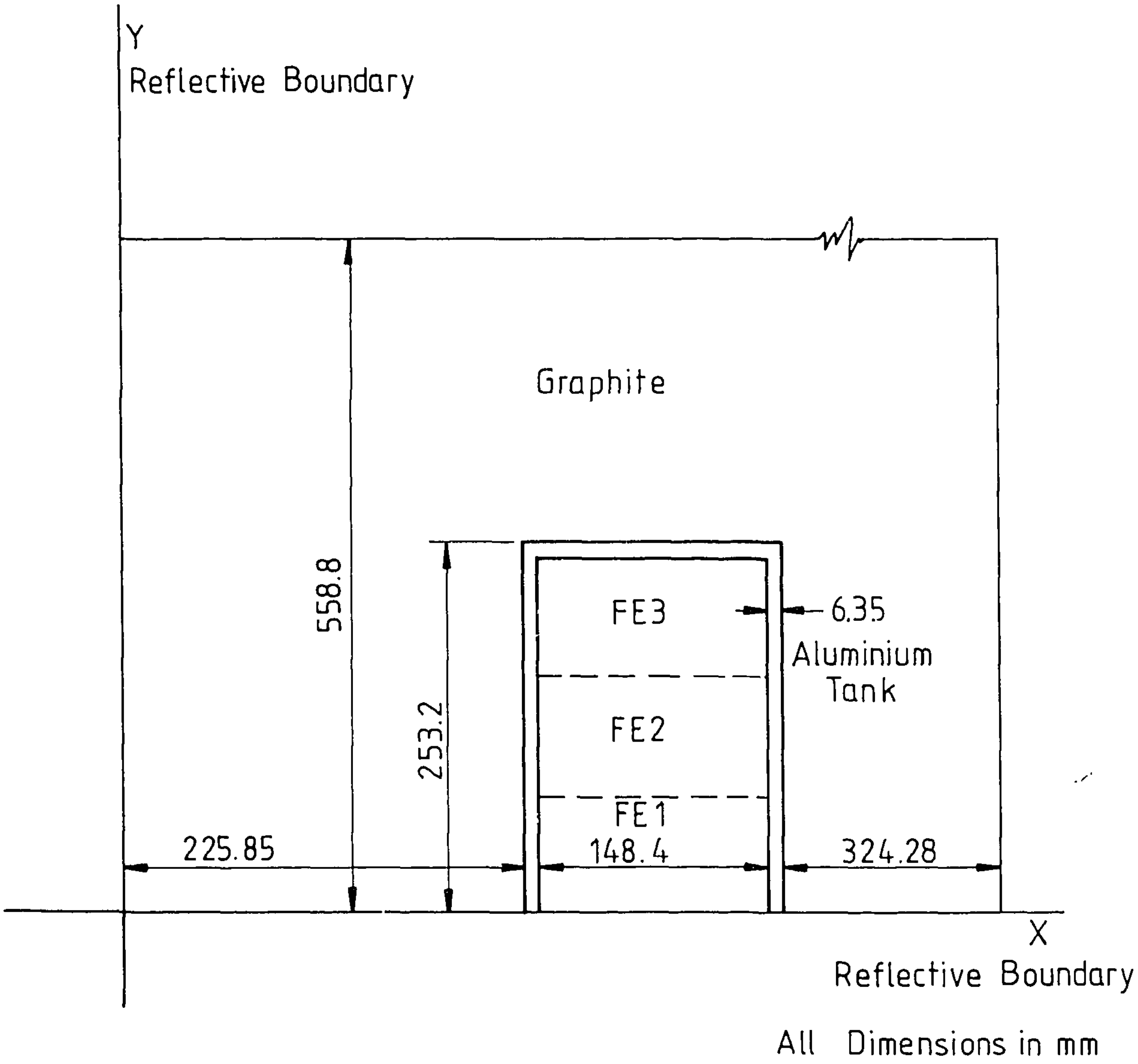

FIGURE 5. DIMENSIONS FOR THE REACTOR CALCULATION

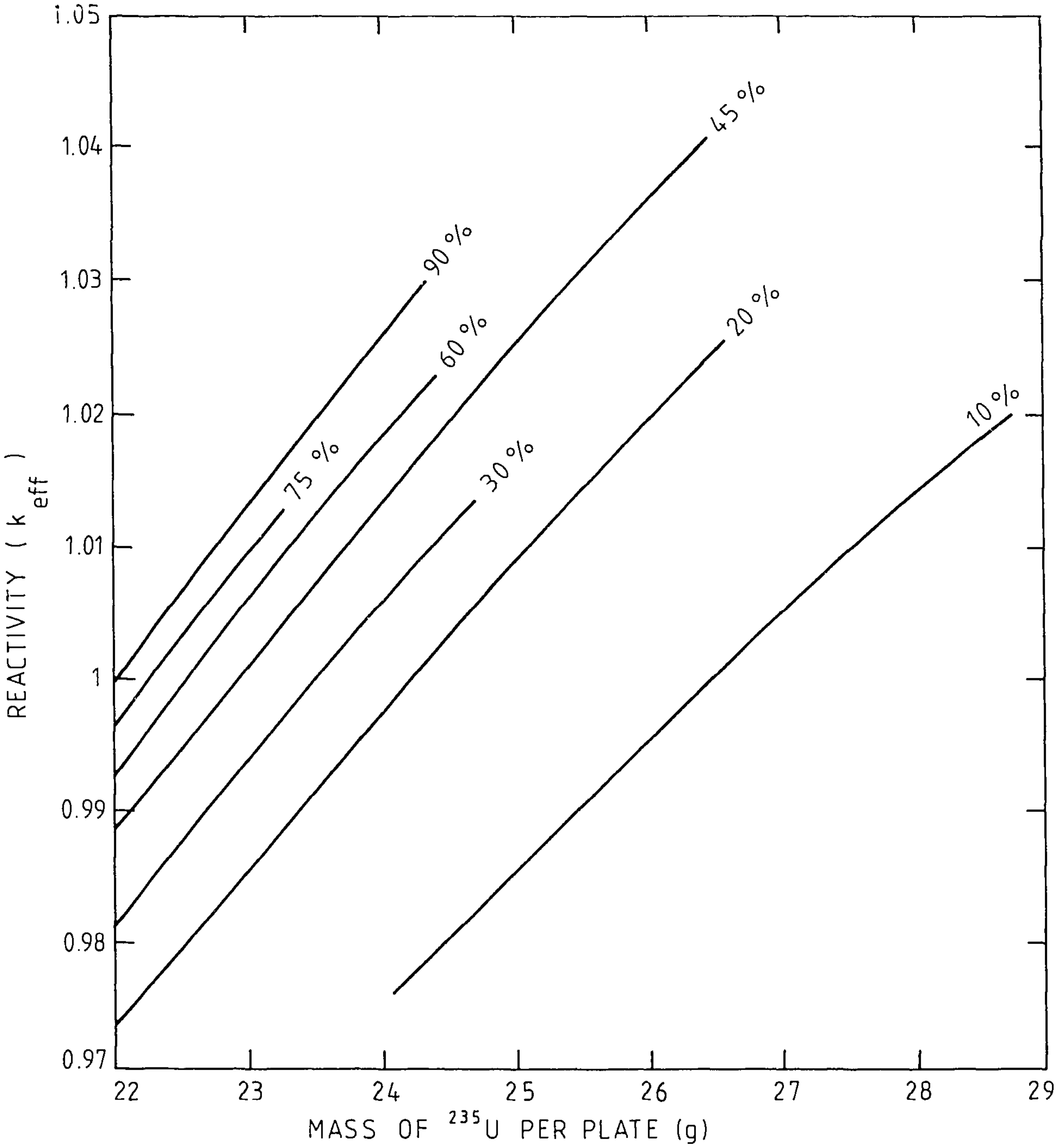

FIGURE 6. MASS OF ^{235}U PER PLATE

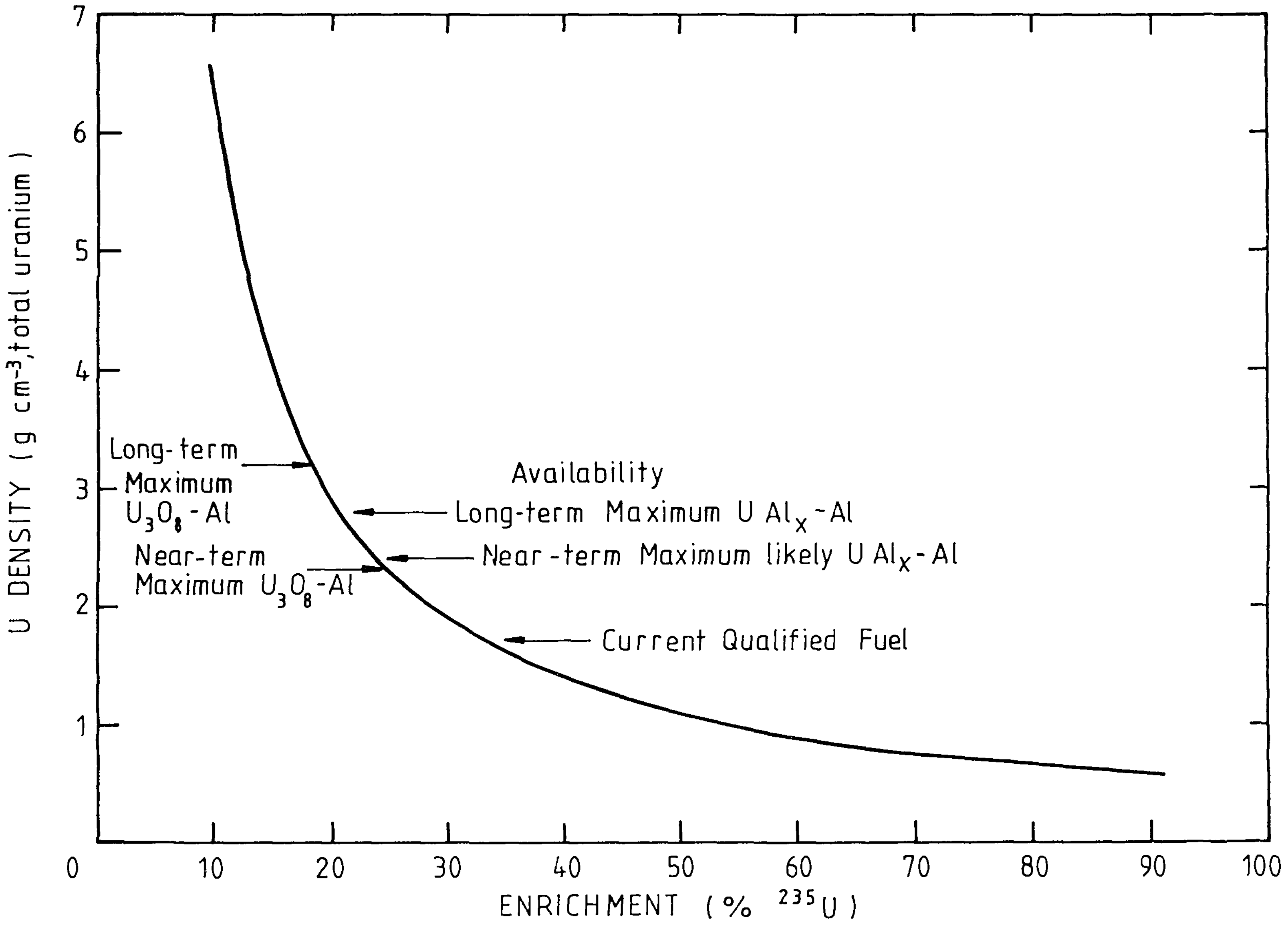

FIGURE 7. FUEL DENSITIES REQUIRED TO REPLACE STANDARD FUEL (90% ENRICHED) WITH NO CHANGES IN FUEL GEOMETRY

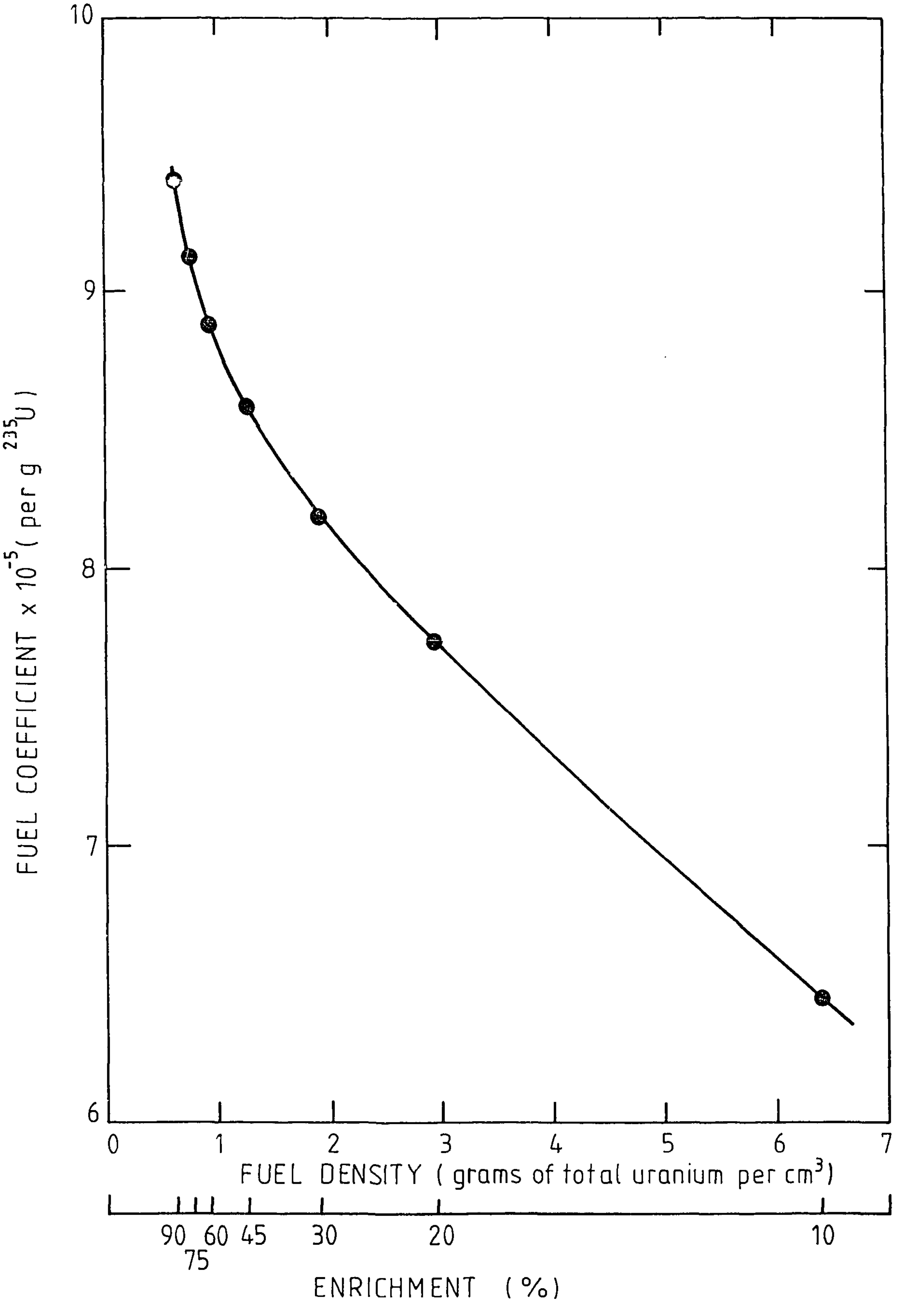

FIGURE 8. REPLACEMENT OF 90% ENRICHED FUEL IN MOATA AT CONSTANT REACTIVITY. VARIATION OF FUEL COEFFICIENT WITH FUEL DENSITY ON ENRICHMENT

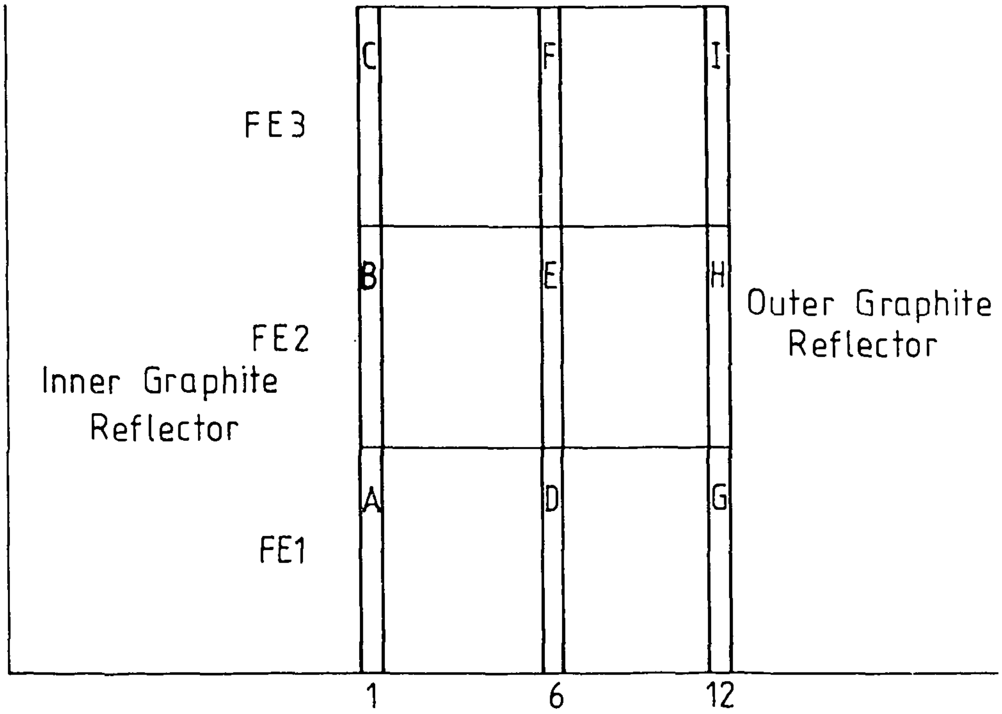

FIGURE 9. FUEL PLATE POSITIONS FOR REPLACEMENT